1RMA: Re-envisioning Remote Memory Access for Multi-tenant Datacenters

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Problem Statement

RDMA is an attractive option for modern datacenter applications due to its low latency and high throughput benefits

- Pilaf(atc13), HERD(sigcomm14), FaSST(osdi16), FaRM(nsdi18), PolarFS(vldb18) ….

Operationalizing RDMA in multi-tenant datacenters uncovered deployment issues:

- Connection-orientedness leading to poor scalability, ordering and failure semantics
- Not amenable to support key security management operations (e.g., rotating encryption keys)
- Not amenable to rapid iteration due to key algorithms (e.g., congestion control) baked in hardware

How do we design remote memory access for multi-tenant datacenters?

1RMA: Remote Memory Access for Multi-tenant Datacenters

1RMA NIC Hardware

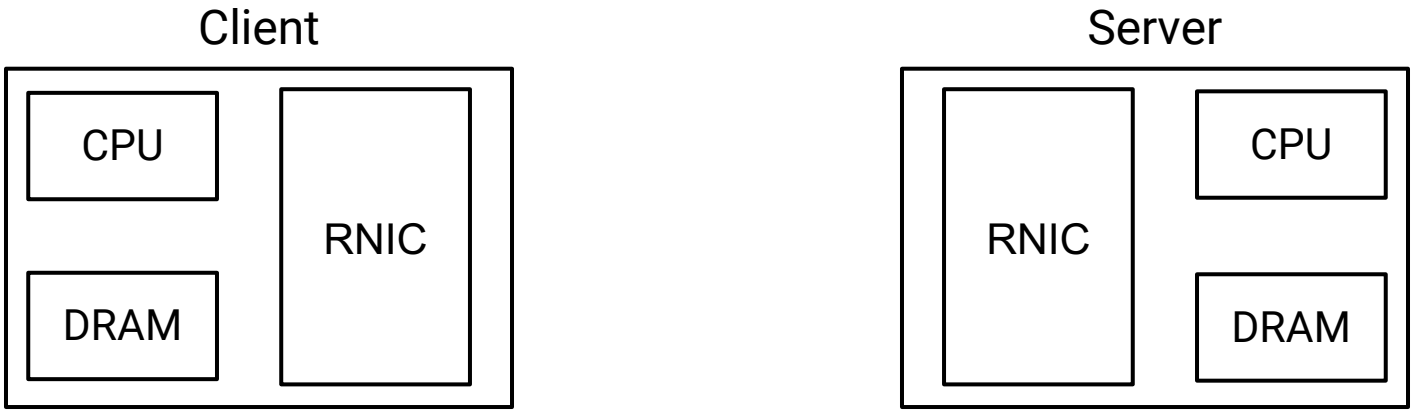
- Connection-free and fixed-function hardware
- Line-rate crypto for unified access control, integrity and privacy with first class support for encryption key rotation
- Aids software by providing delay measurements and fast failure notifications

1RMA Software

- Implements congestion control and op management (e.g., failure recovery)

What is RDMA?

RDMA allows direct access to the memory of a remote machine resulting in low latency and high throughput



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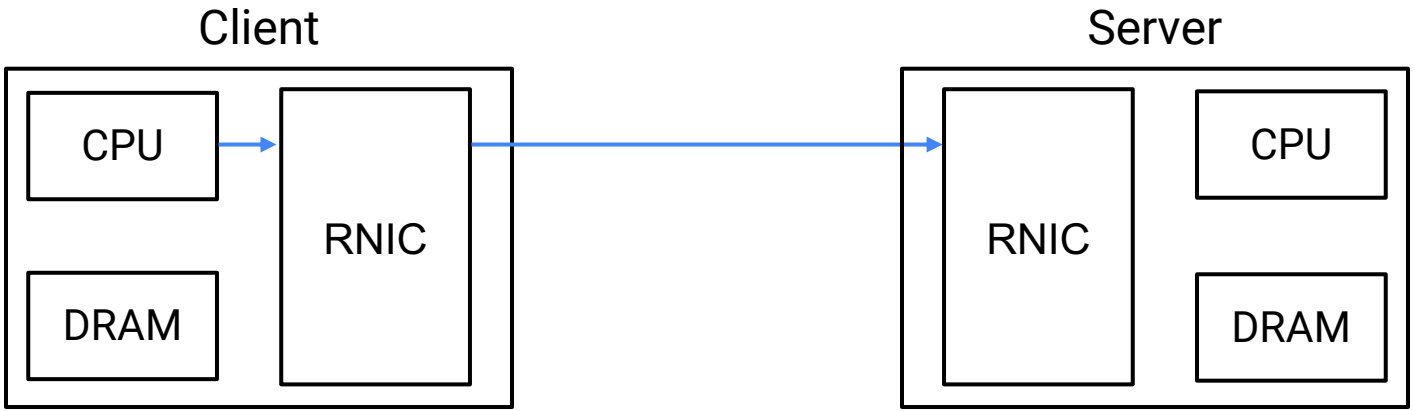

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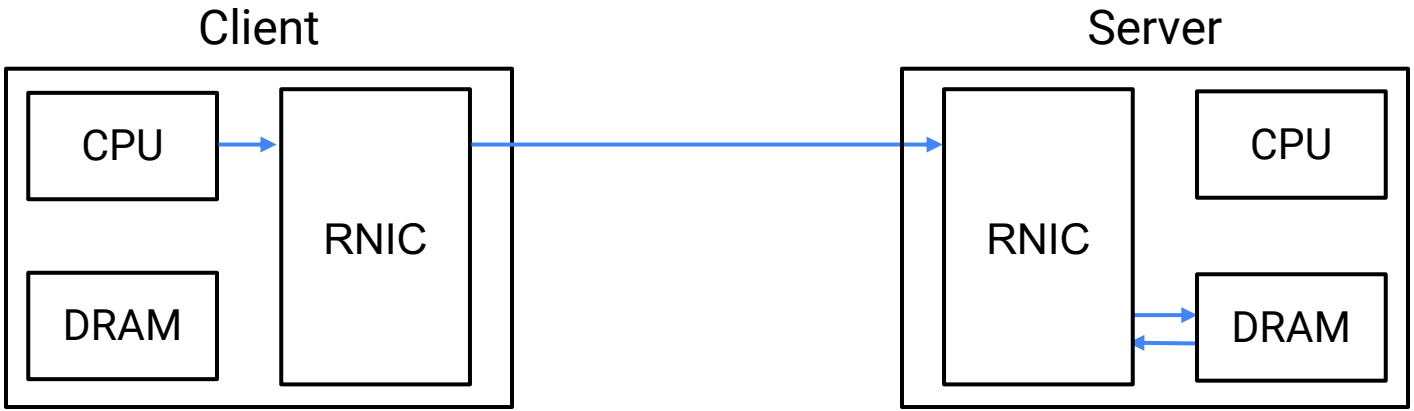

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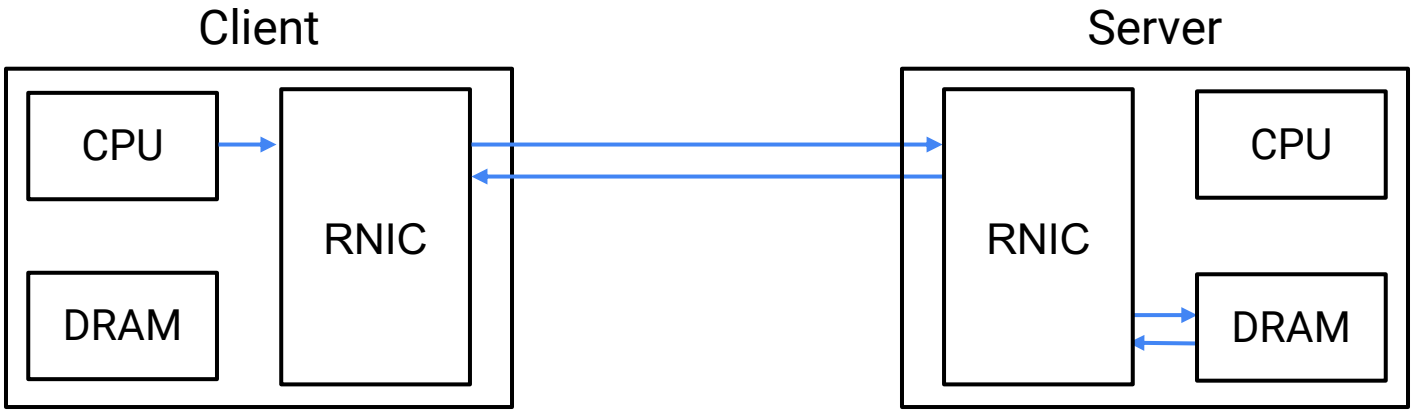

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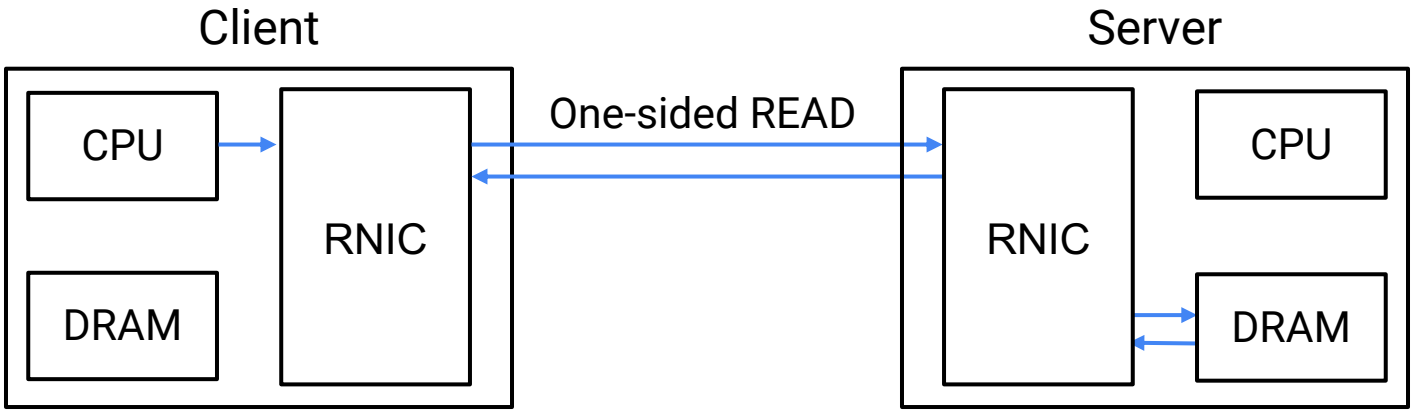

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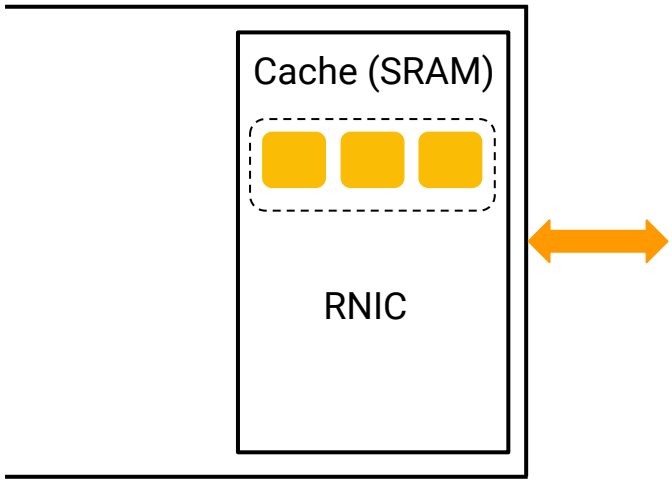

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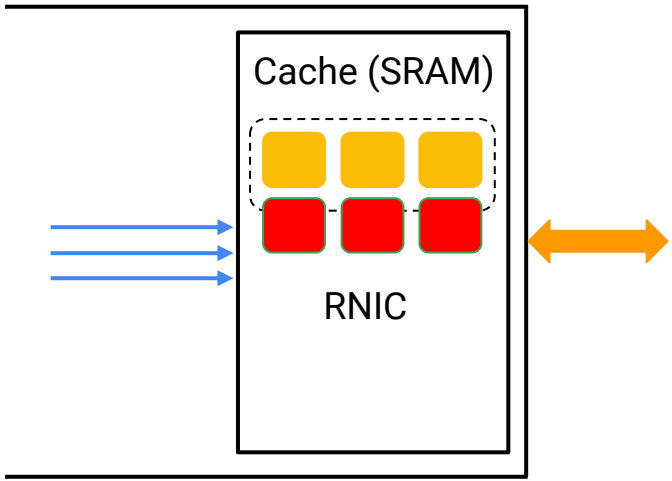

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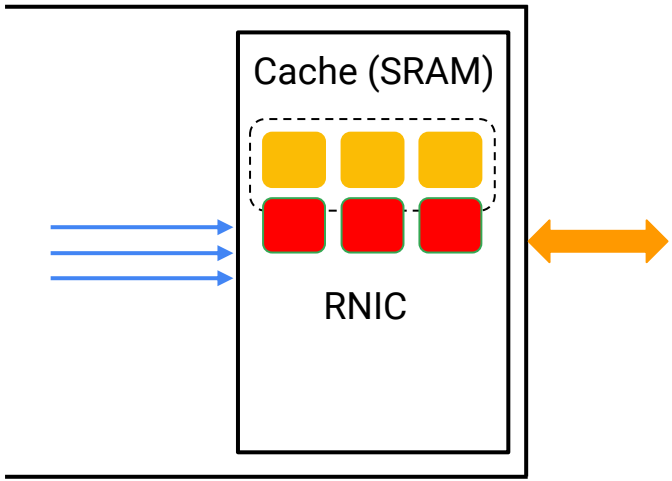

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Performance Cliffs

High Unpredictable Latencies

Reduced Throughput

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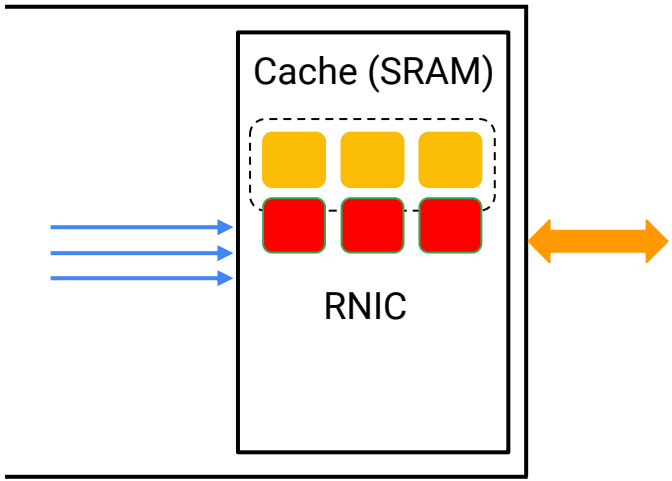

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Critical applications can be stranded due to connection exhaustion

RDMA Challenge #1: Pathologies due to Connections

Address connection scalability and performance issues via **connection sharing**

- Multiplexing independent workloads on the same connection

Connection sharing leads to **induced ordering**

- RDMA requires FIFO execution of ops (same type) within a single connection

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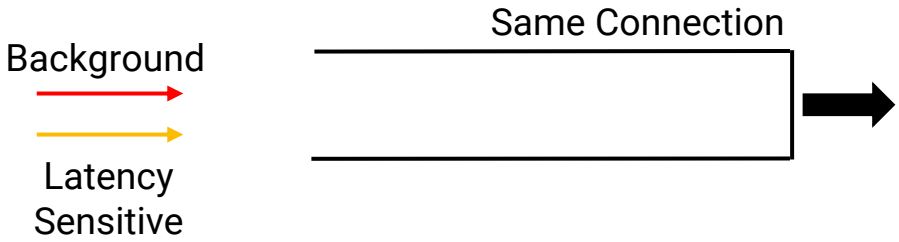

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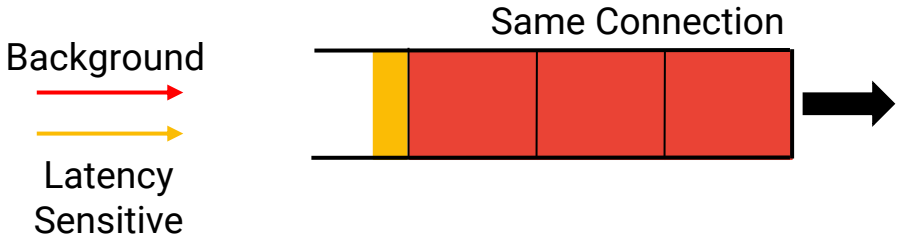

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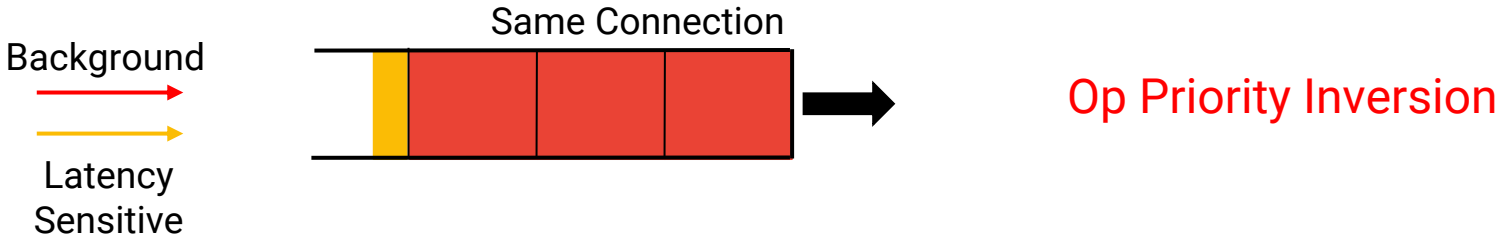

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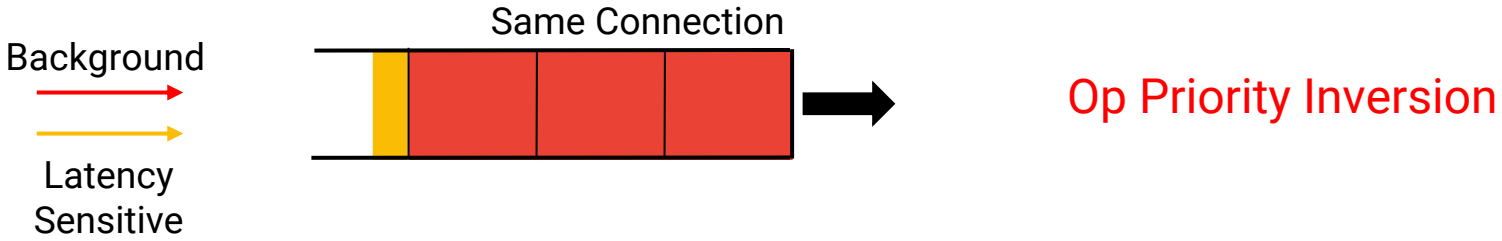

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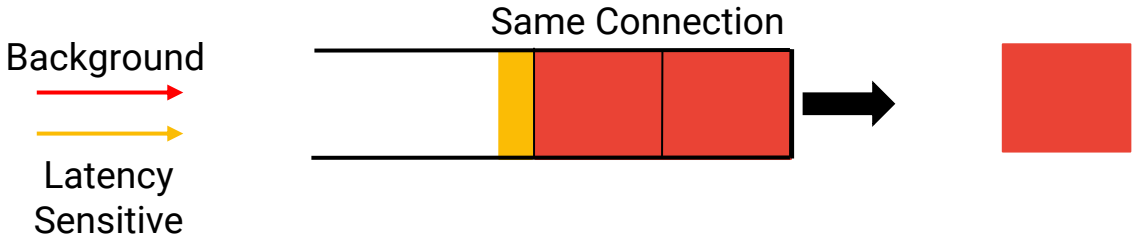

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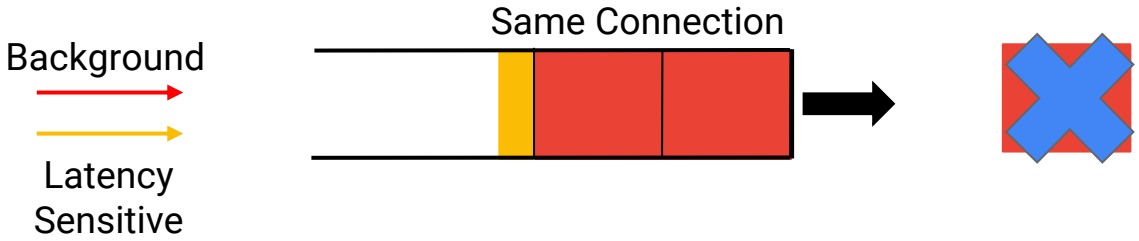

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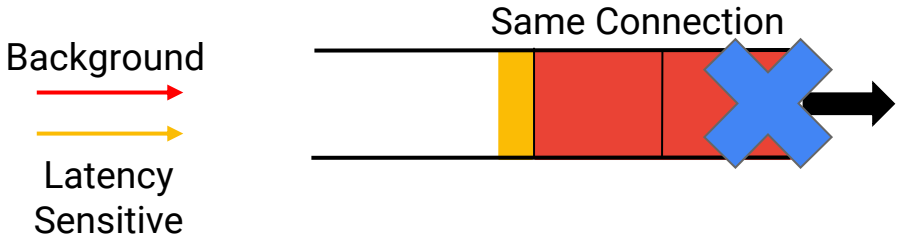

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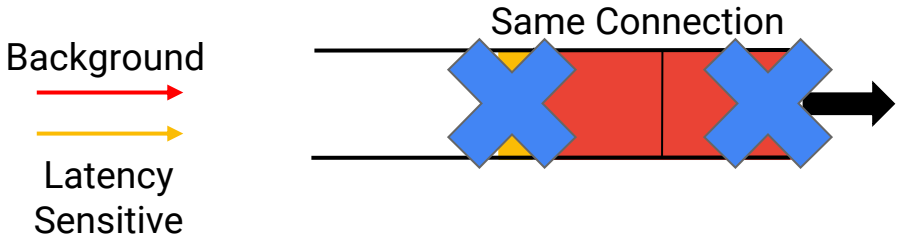

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RDMA Challenge #2: Connection-centric Security

RDMA ties access control to connections through protection domains

RDMA does not provide any ready means to manage encryption keys

- Applications that seek to rotate the keys are required to reconnect leading to an inordinate period of unavailability

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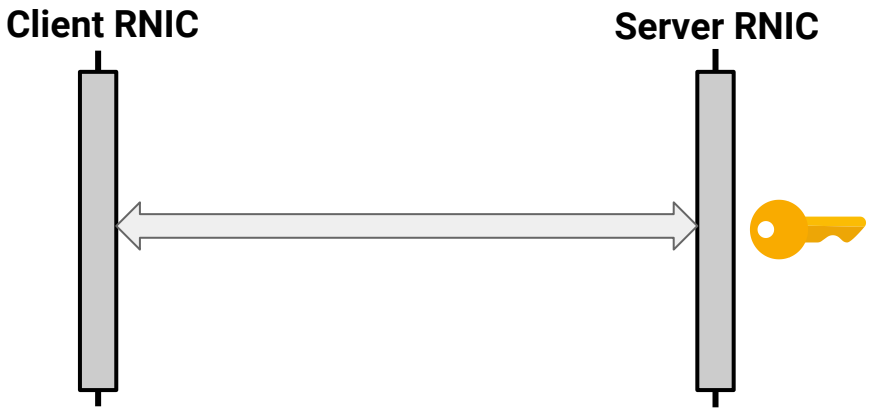

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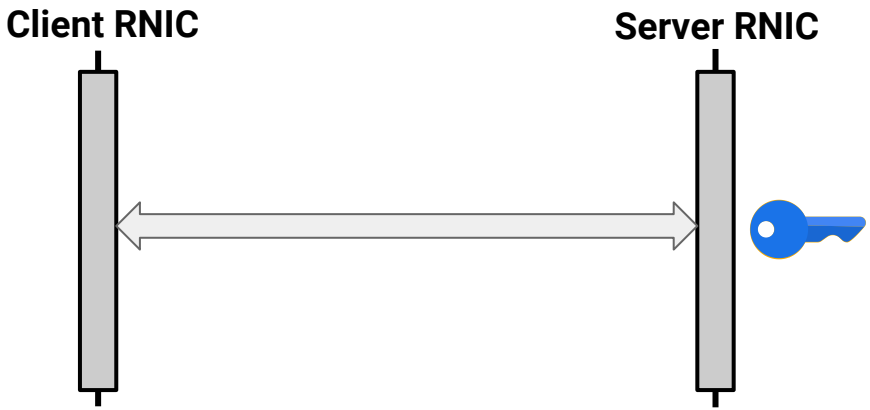

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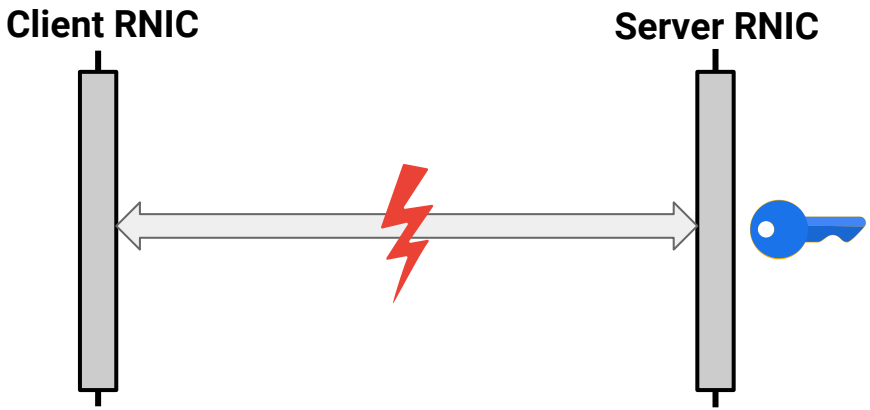

RDMA Challenge #3: Rigid Congestion Control and Loss Recovery

RoCE enables RDMA over Ethernet fabric and uses priority flow control (PFC) to provide a near-lossless network

PFC is untenable in commercial datacenters due to its operational hazards

- Practical DCB for Improved Datacenter Network(infocom14)
- RDMA over Commodity Ethernet at Scale(sigcomm16)

Recent proposals reduce reliance on PFC

- Bake congestion response in hardware
  - DCQCN(sigcomm15), HPCC(sigcomm19)
- Bake sophisticated loss recovery in hardware
  - IRN(sigcomm18) : selective retransmission instead of go-back-N

Not amenable to changes post-deployment

RDMA Challenges: Root Causes

RDMA ill-suited due to its two basic design attributes

Connection Orientedness

Complex policies baked into hardware

1RMA Approach

Judicious division of labor between hardware and software leading to a simple and fixed-function 1RMA NIC aided by 1RMA software

Fixed-function NIC hardware with explicitly allocated resources

- Connection-free independent ops
- Explicitly-finite hardware resource pools
- Solicitation

Connection-free security protocol with management ops

Software-driven, hardware-assisted congestion control

1RMA Key Idea #1: Connection-Free Independent Ops

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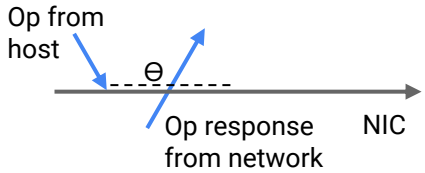

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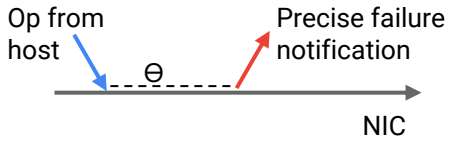

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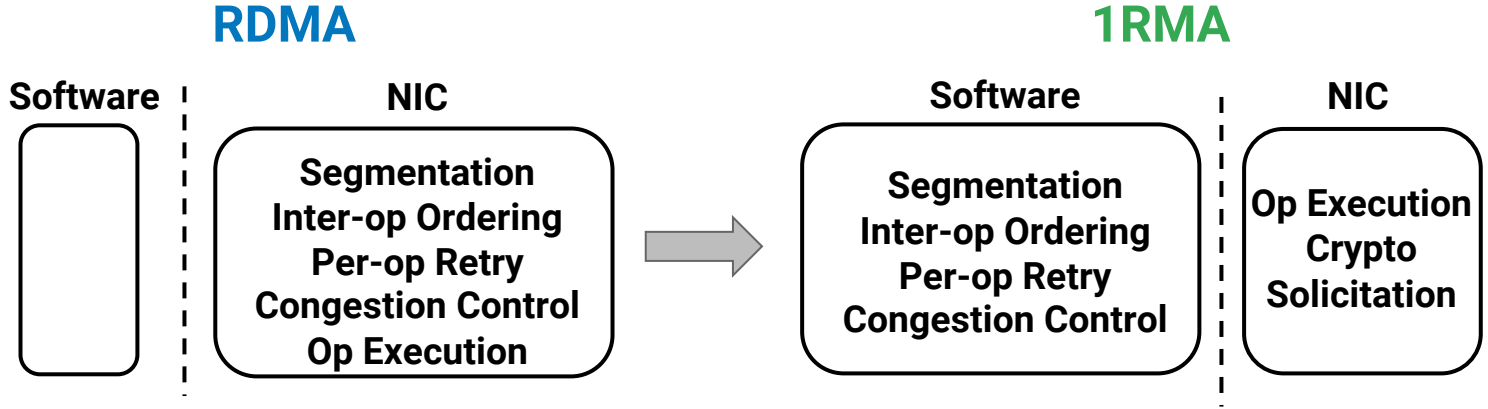

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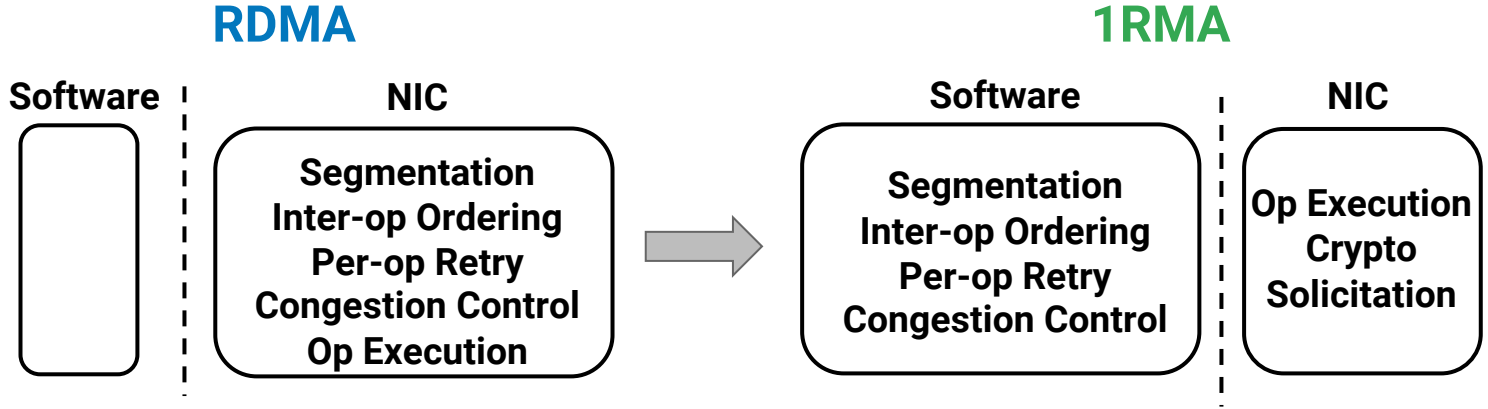

1RMA NIC state does not grow with endpoint pairs

1RMA Key Idea #2: Explicitly-Finite NIC Resource Pools

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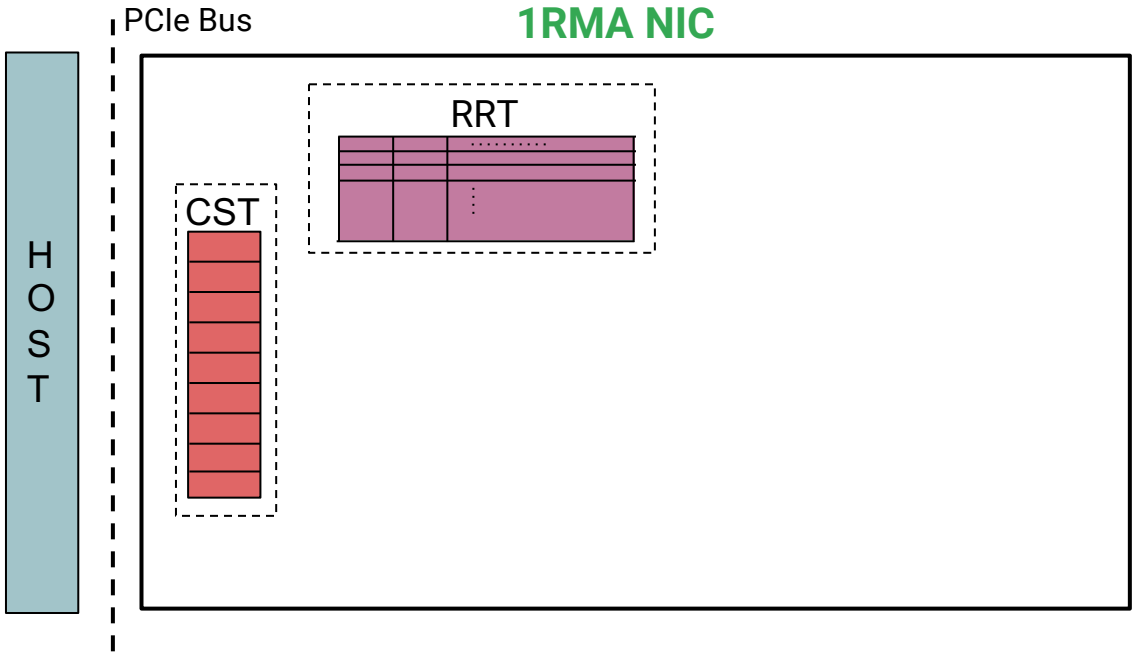

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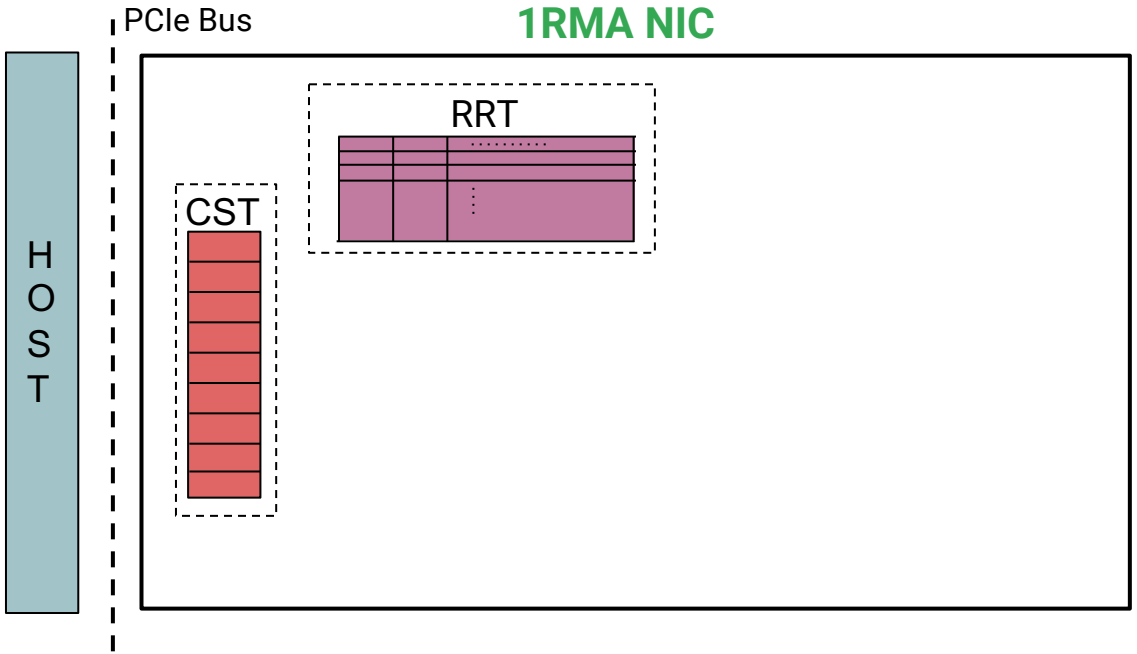

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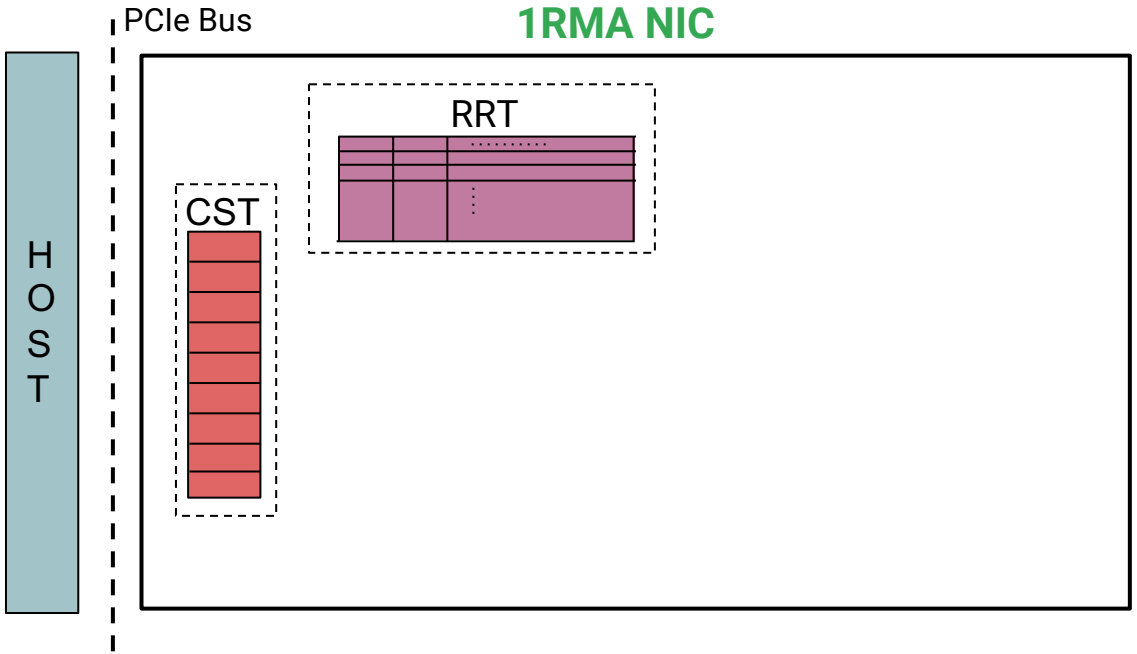

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Resource allocation based on business priorities

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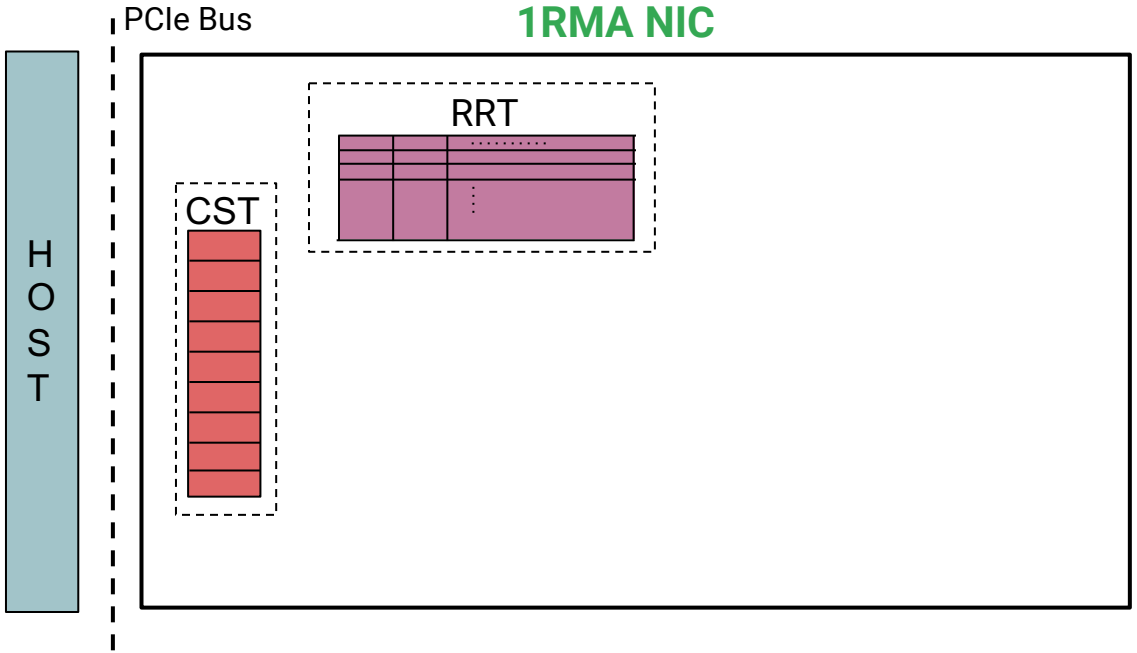

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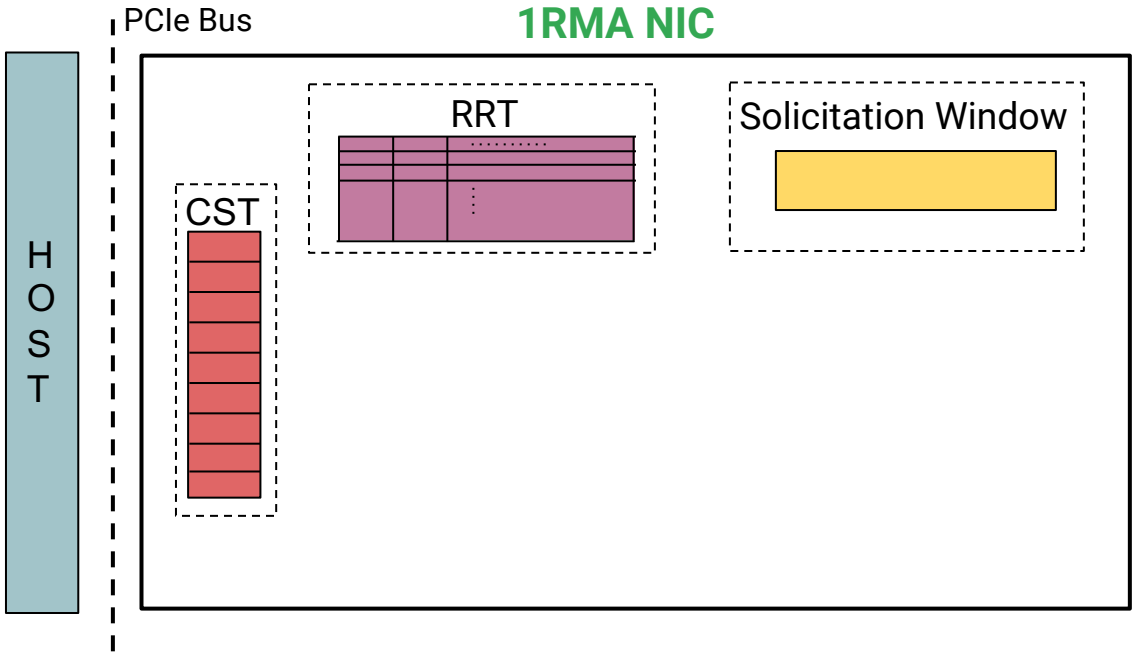

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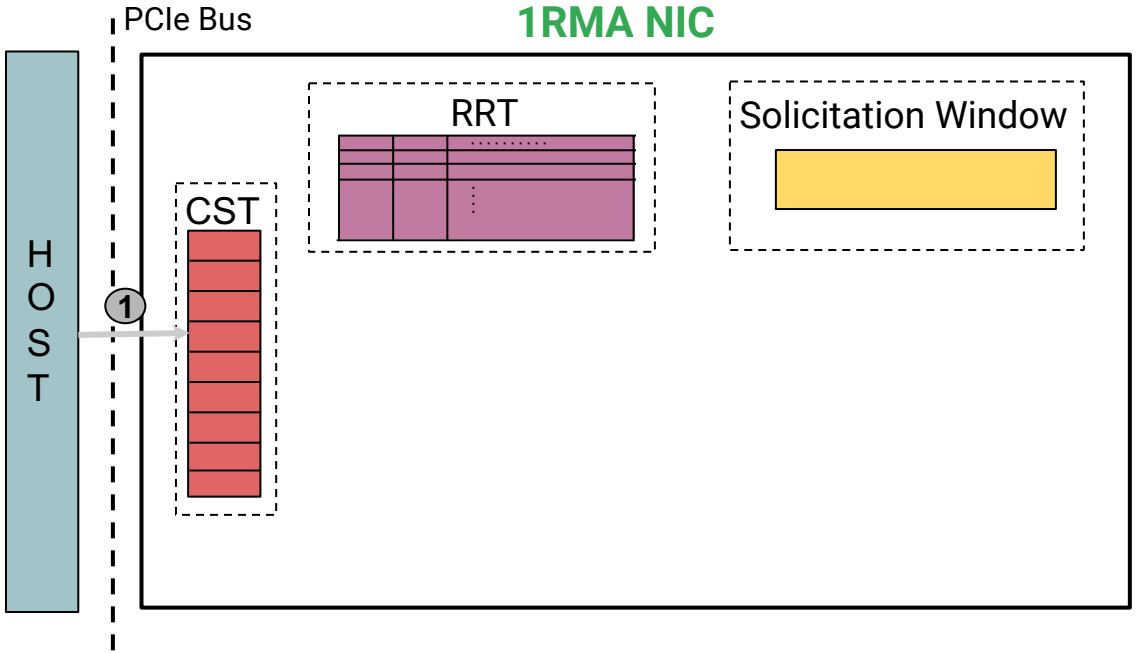

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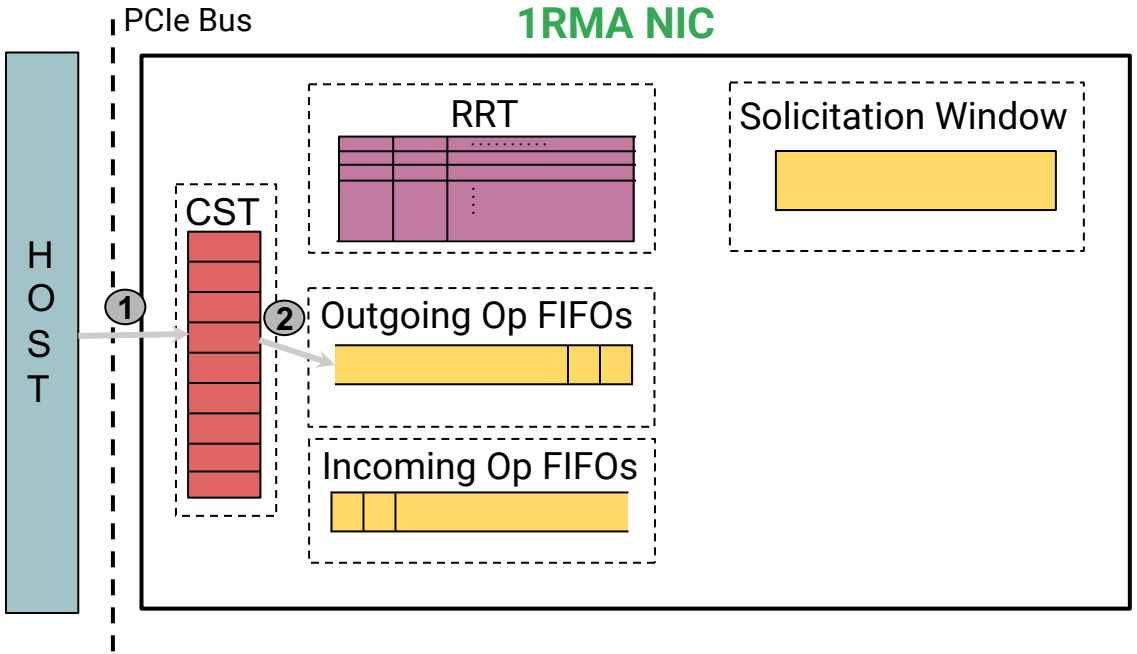

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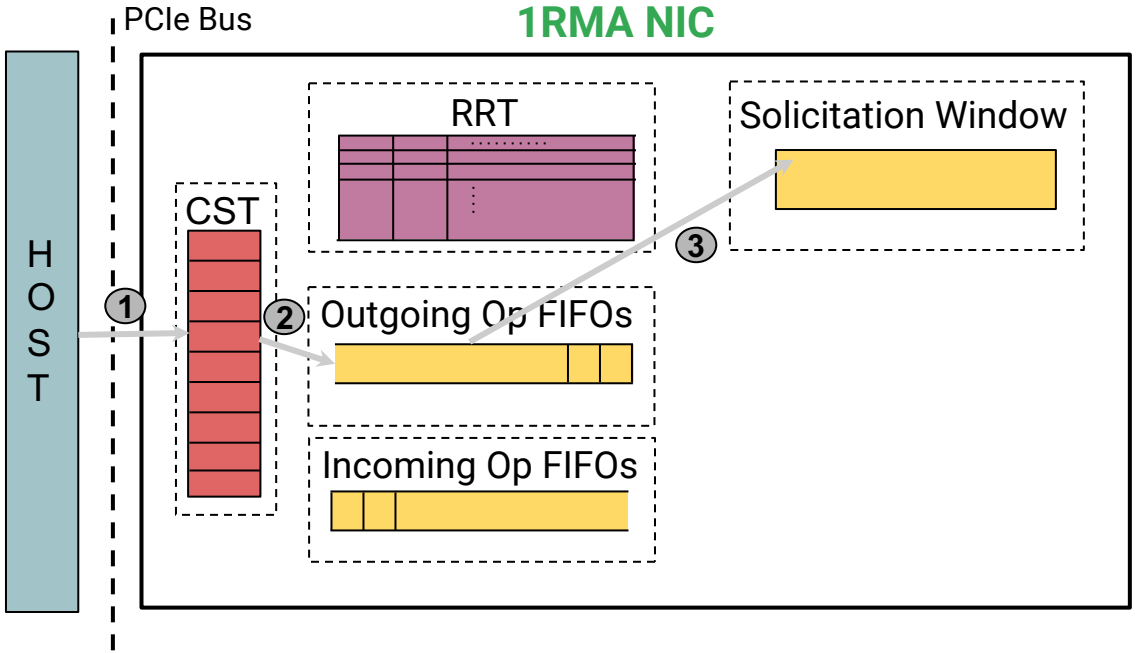

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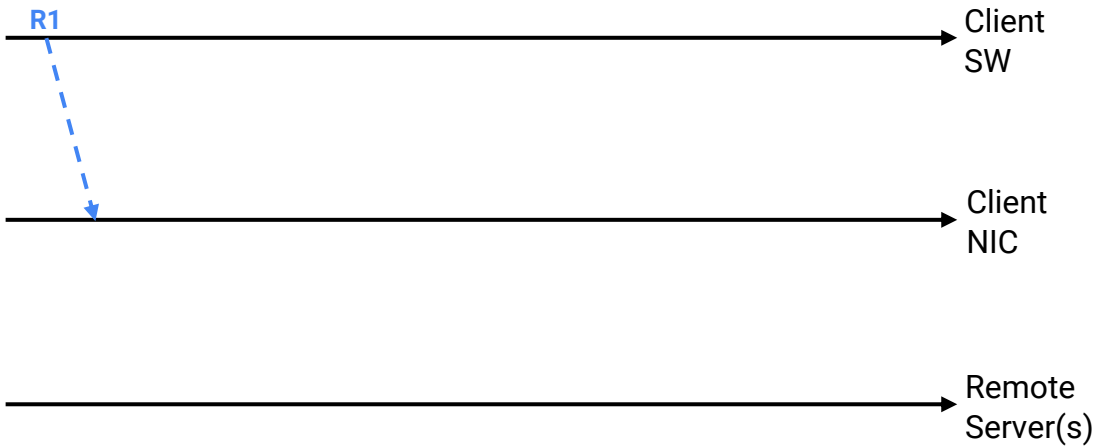

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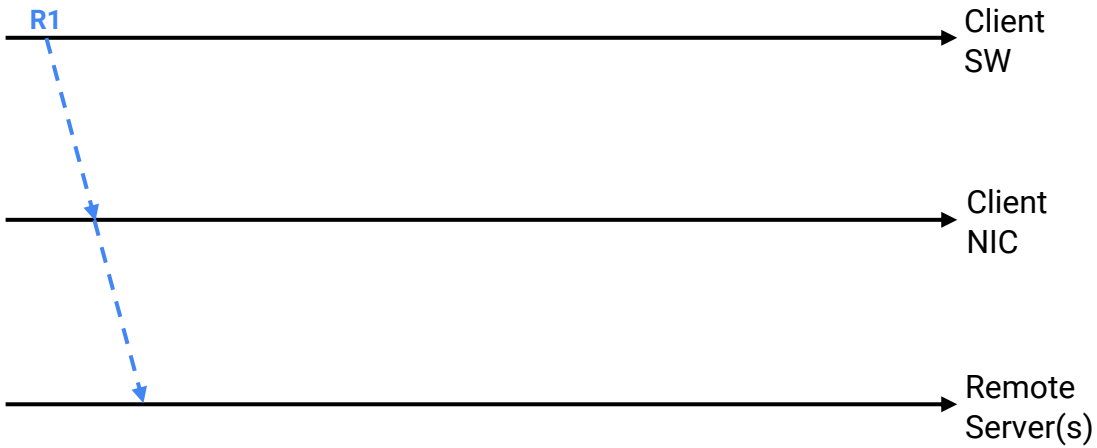

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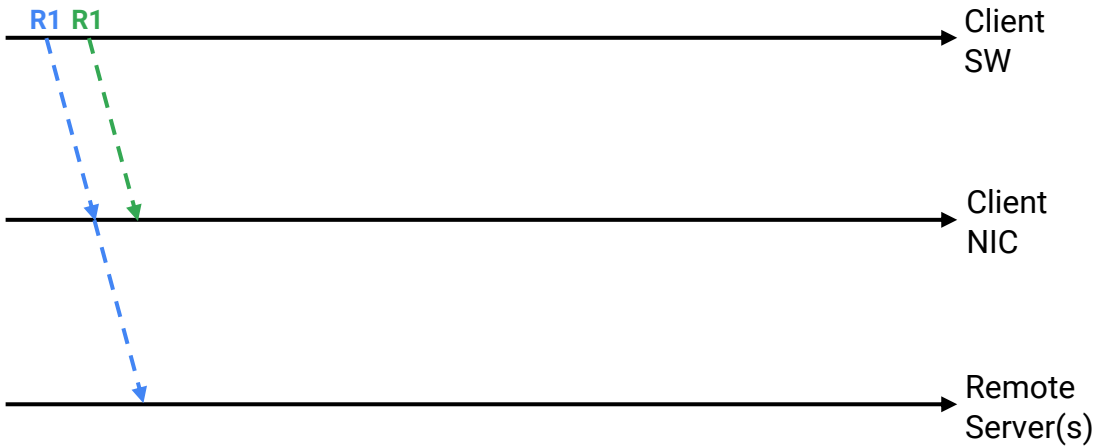

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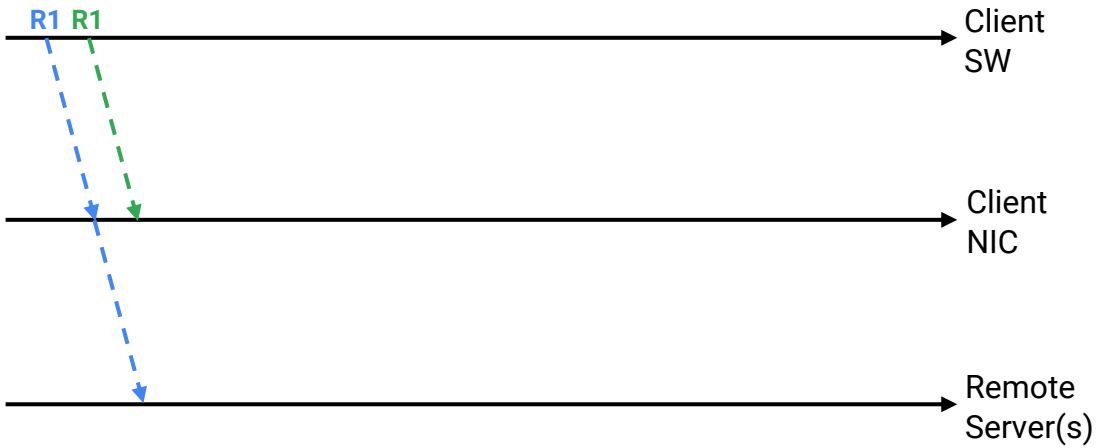

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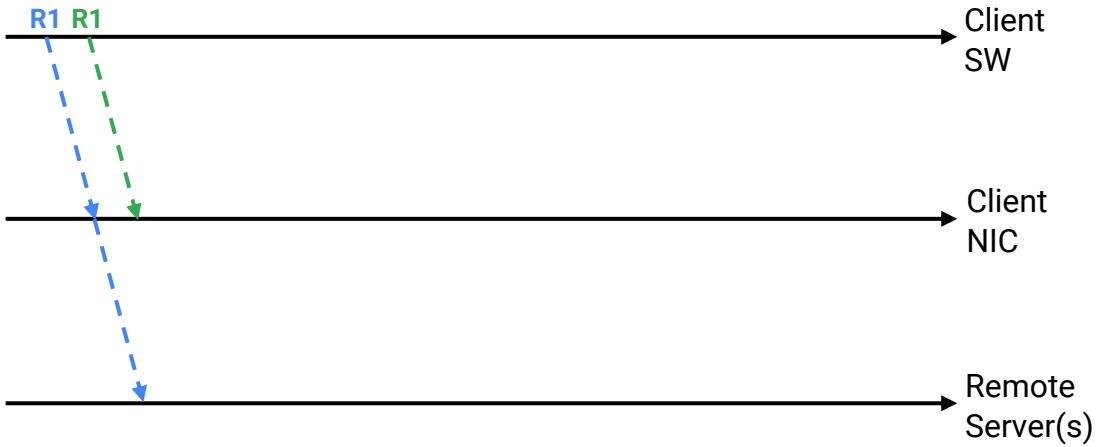

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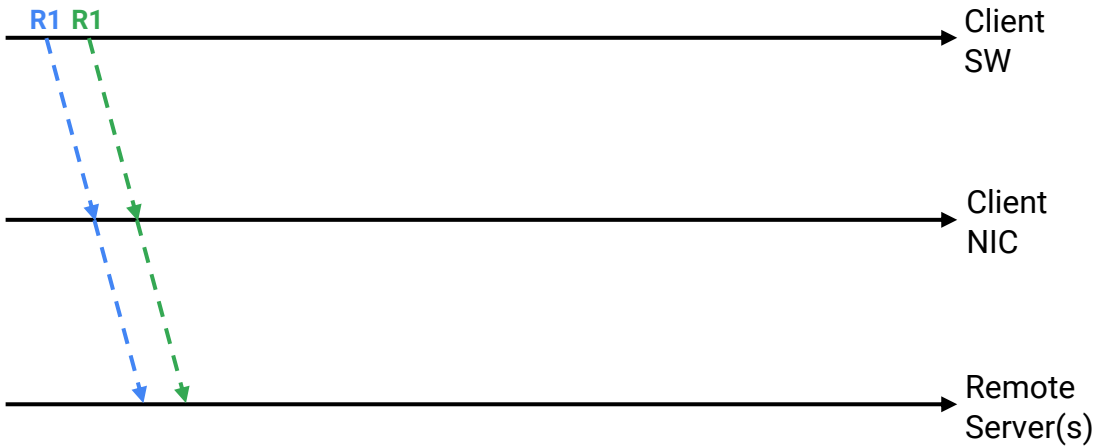

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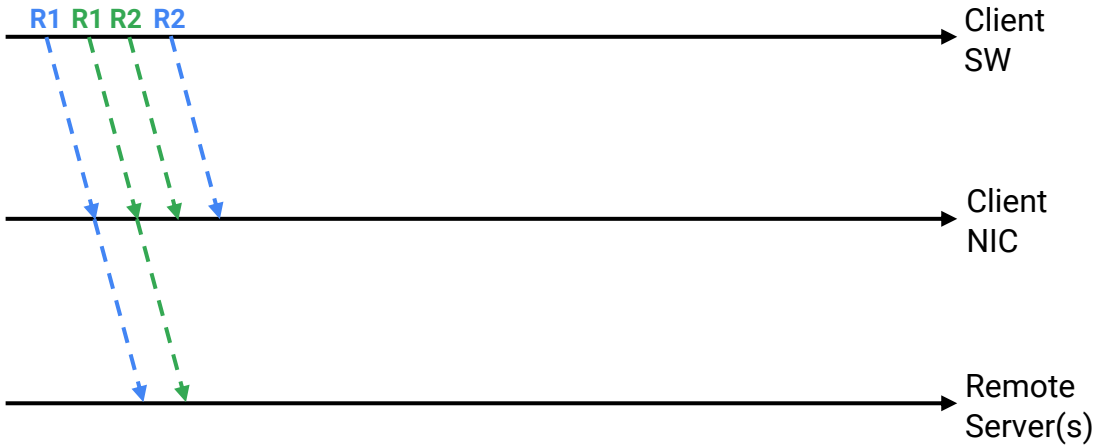

Room in solicitation window?

Solicitation Window

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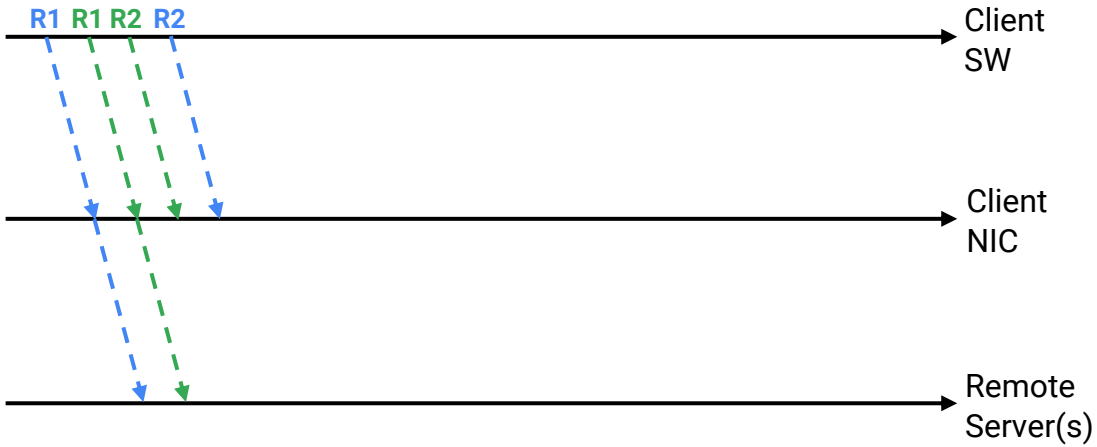

Room in solicitation window? **No**

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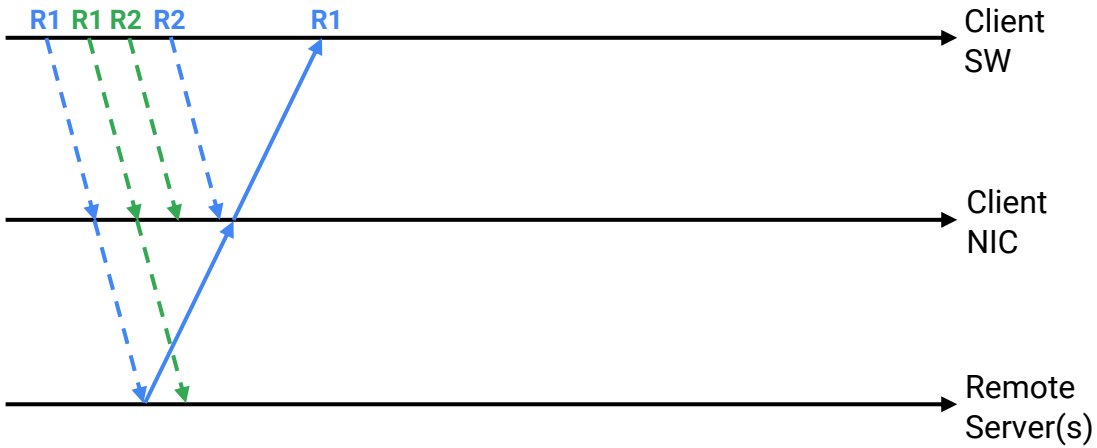

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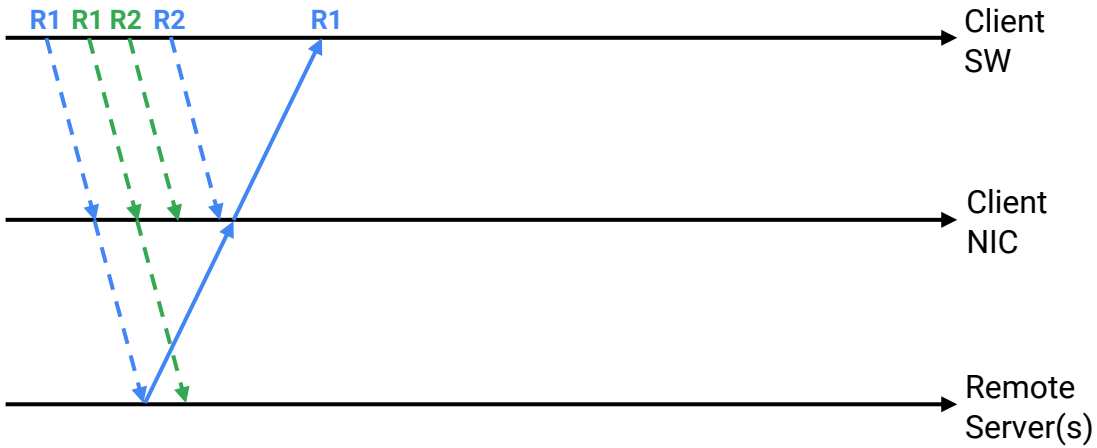

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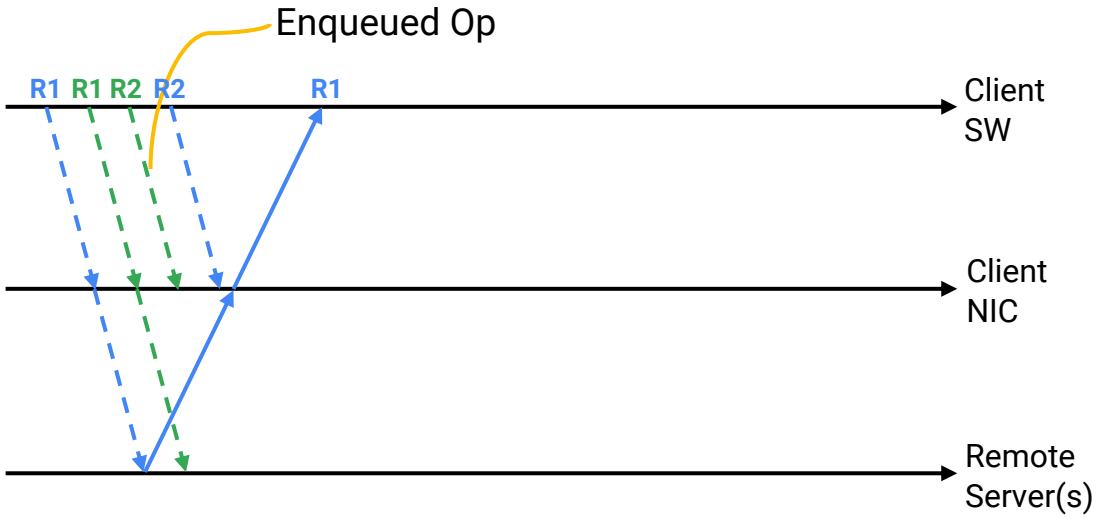

Room in solicitation window? **Yes**

Solicitation Window

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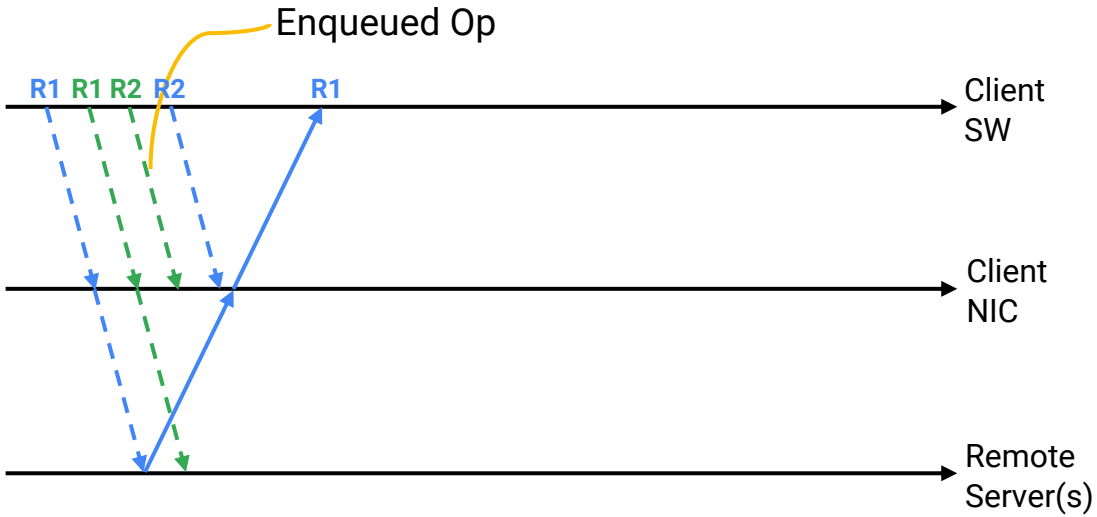

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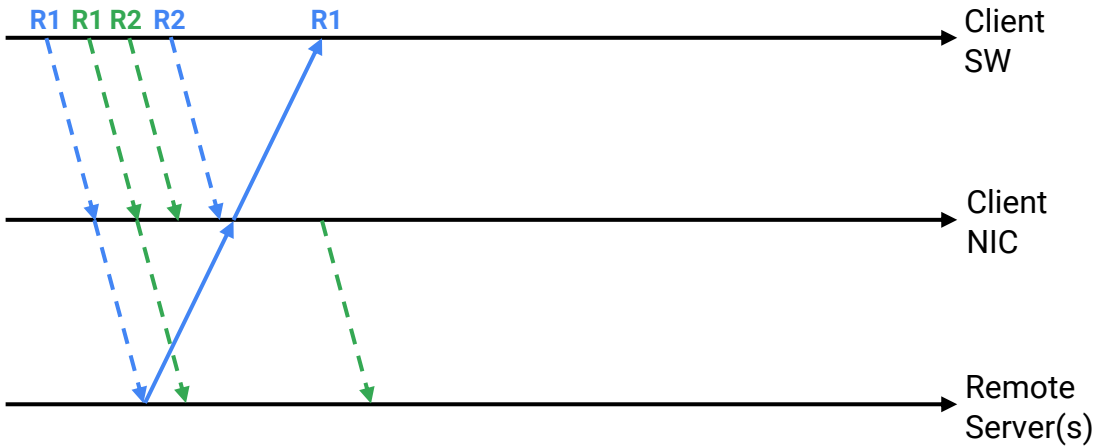

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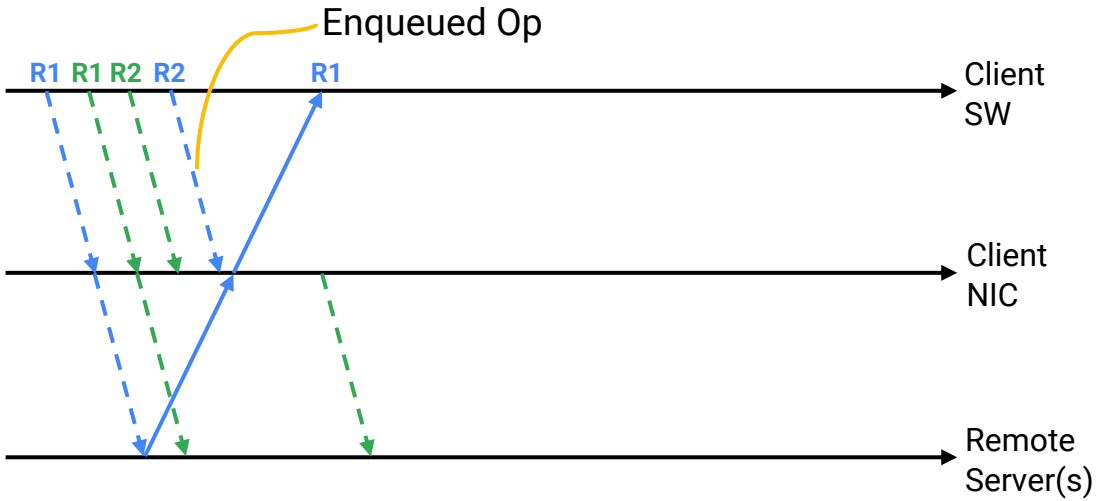

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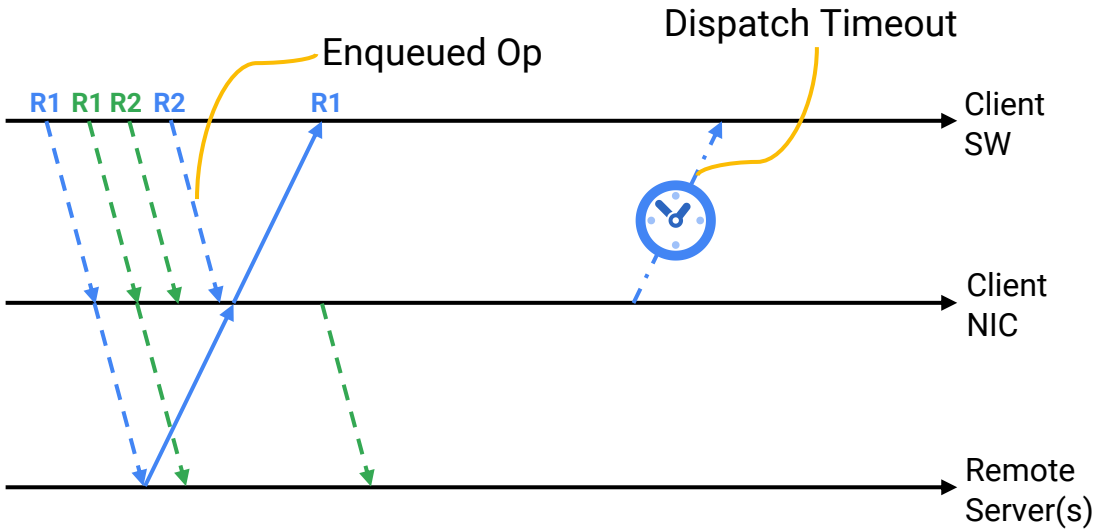

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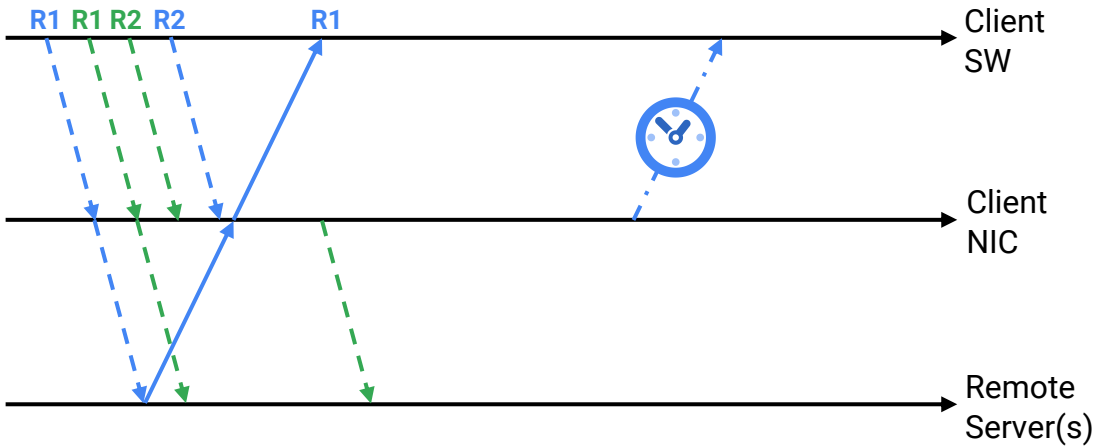

Solicitation Window

Sized based on bandwidth delay product

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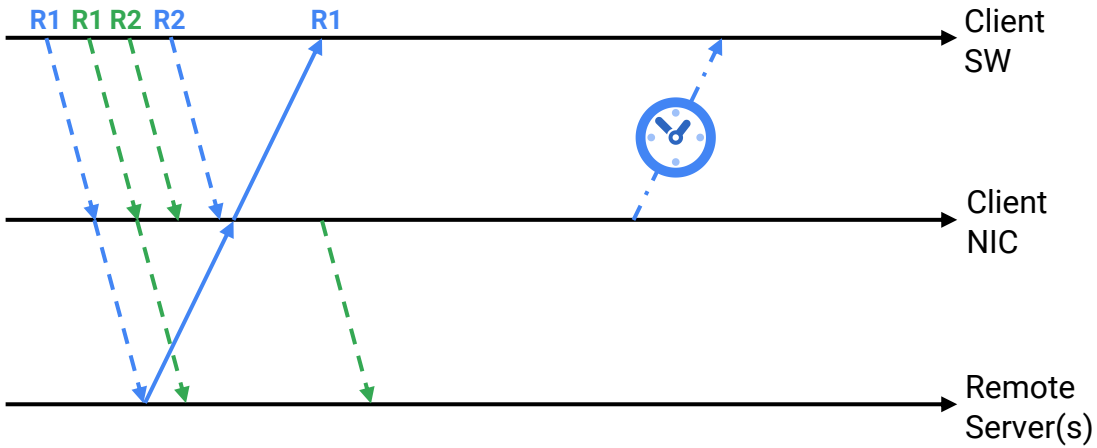
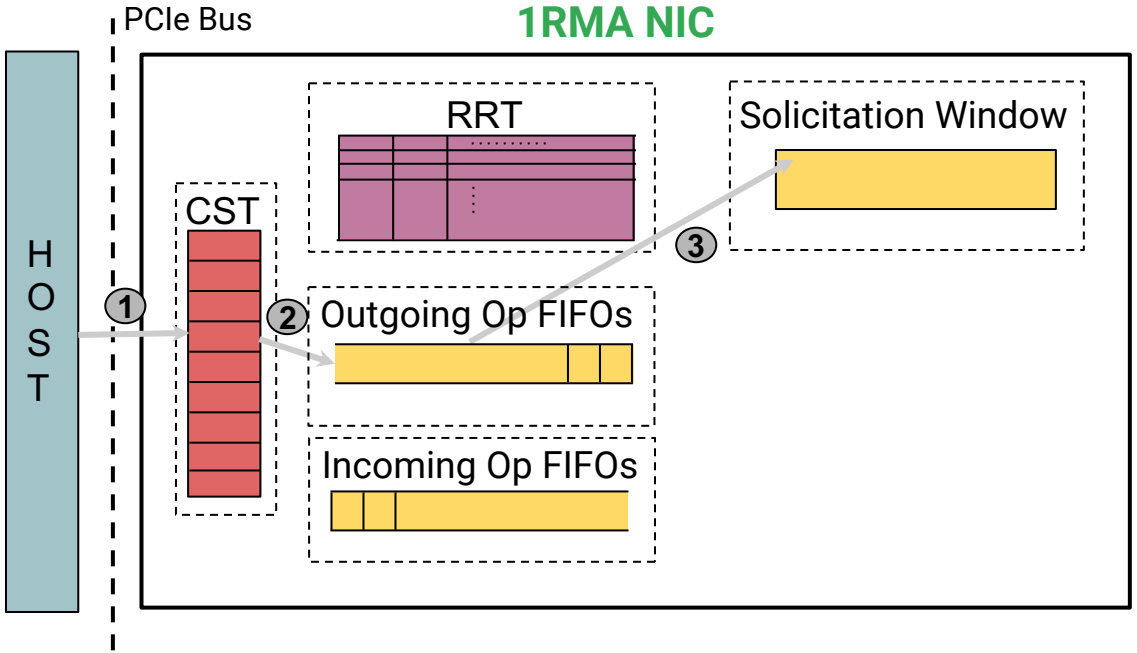


Solicitation Window

Sized based on bandwidth delay product

Limits the severity of sudden incasts by bounding the number of inbound bytes

1RMA Key Idea #4: Connectionless Security with Security Ops



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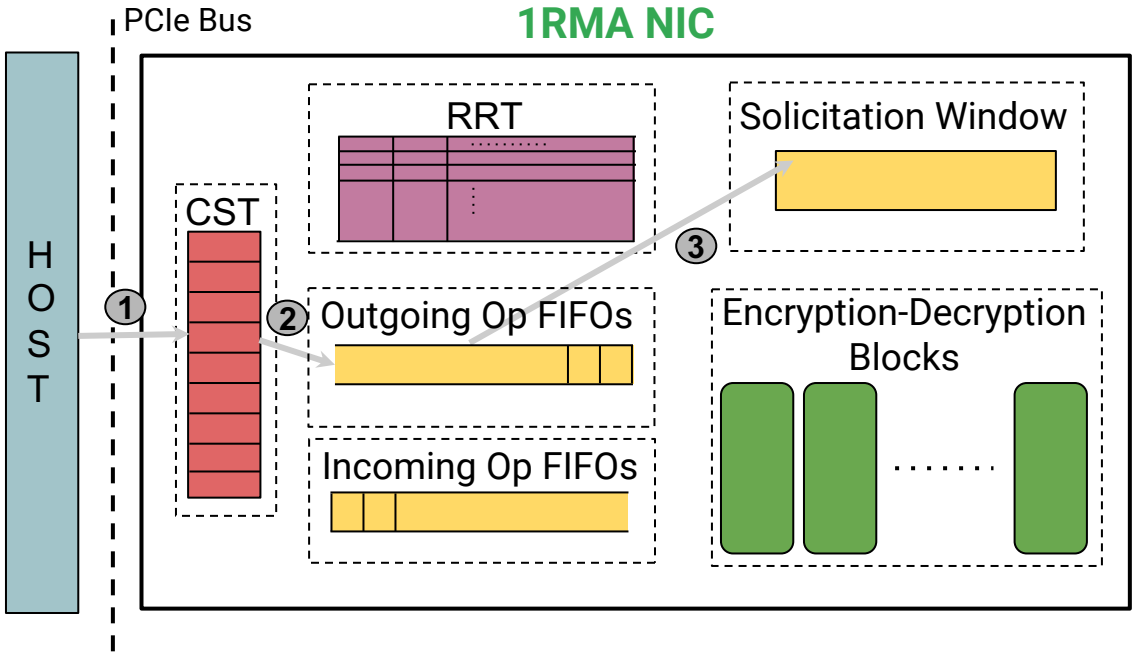
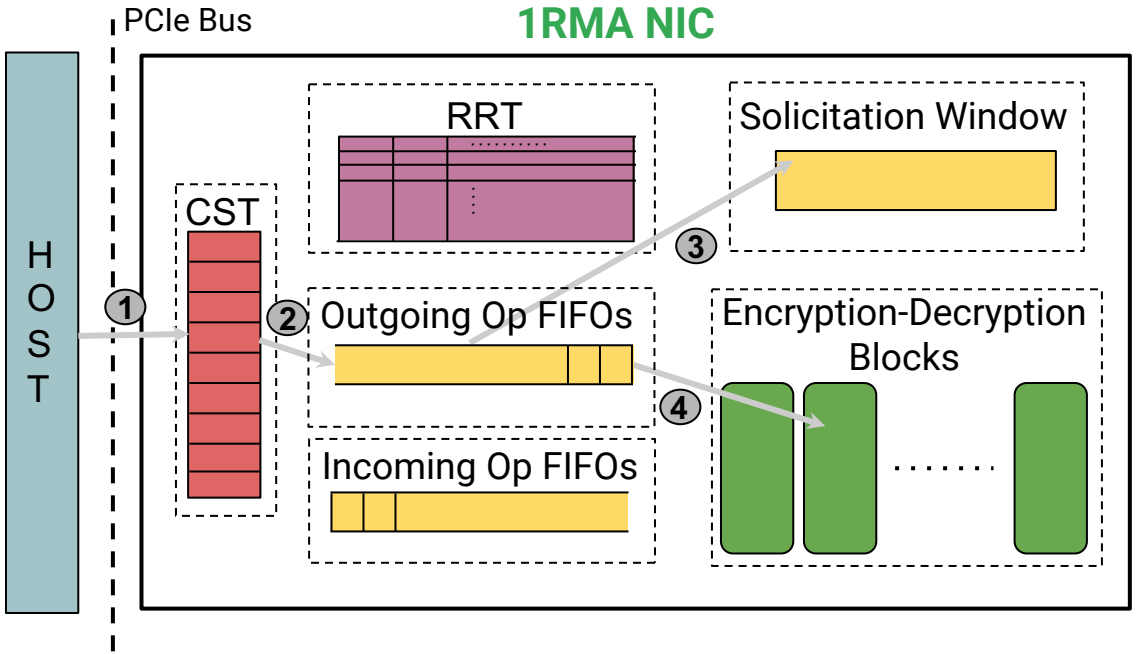


All transfers are **encrypted and signed** in hardware using a novel **connection-free protocol**

1RMA Key Idea #4: Connectionless Security with Security Ops



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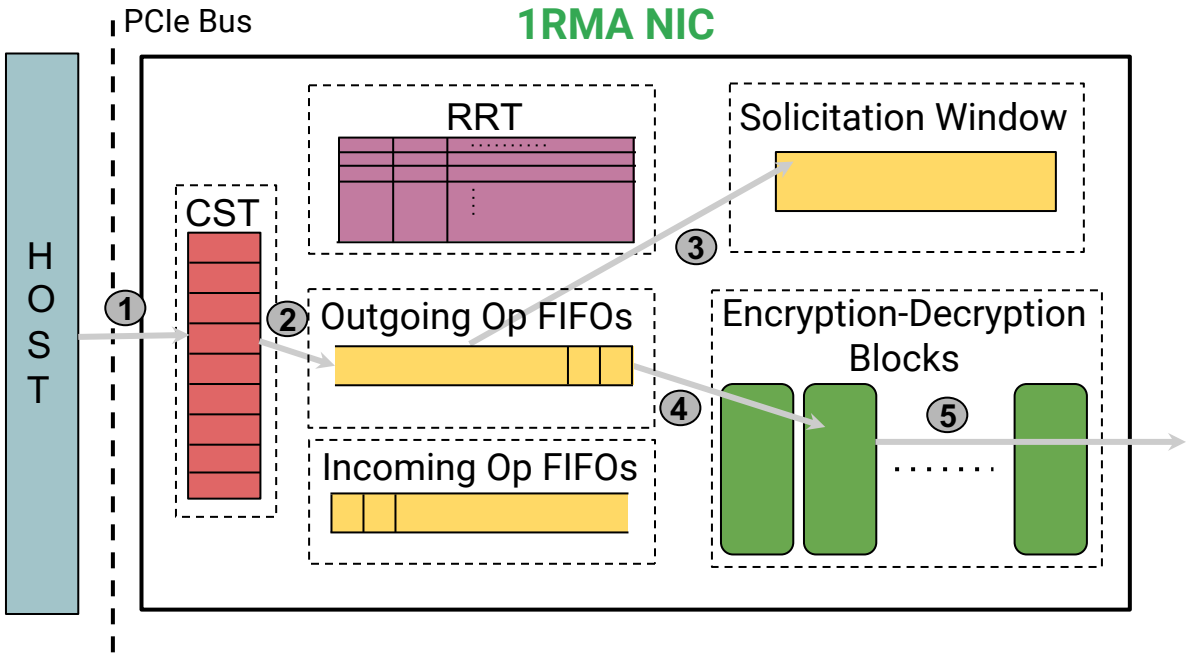

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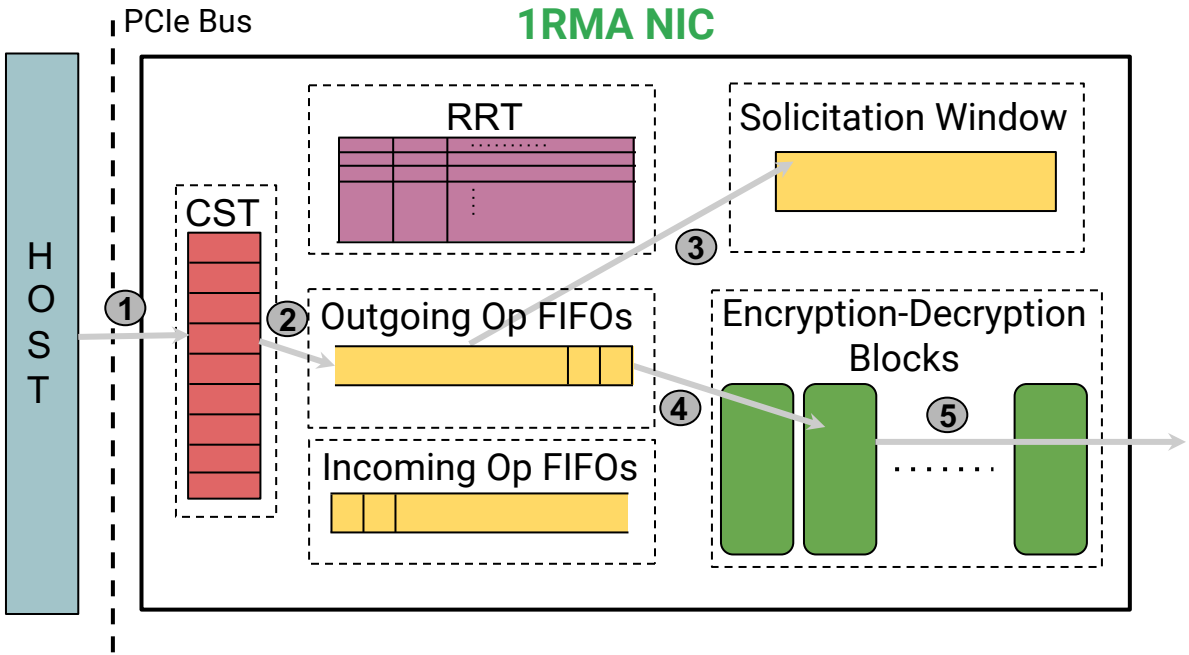
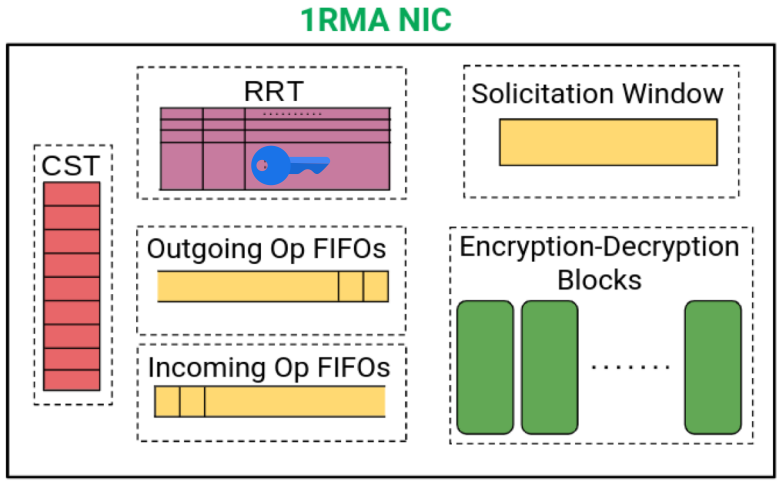


All transfers are **encrypted and signed** in hardware using a novel **connection-free protocol**

1RMA offers a **Rekey op** that provides **support for encryption key rotation**

1RMA Key Idea #4: Connectionless Security with Security Ops



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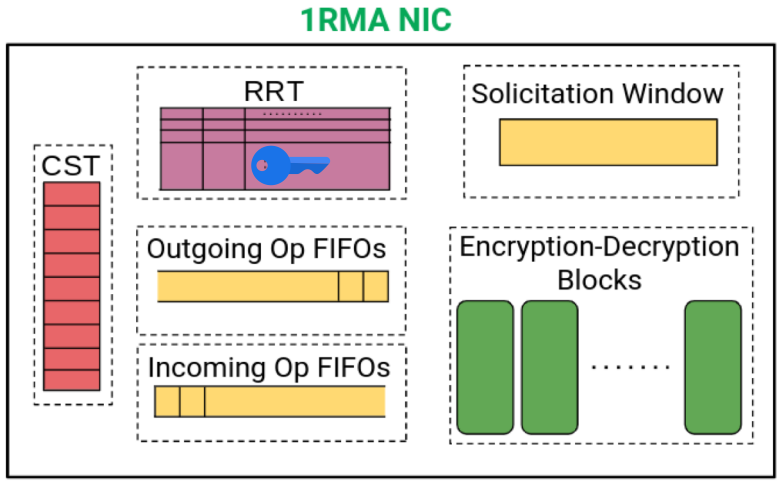
1RMA Key Idea #4: Connectionless Security with Security Ops

Remote Key Rotation Service



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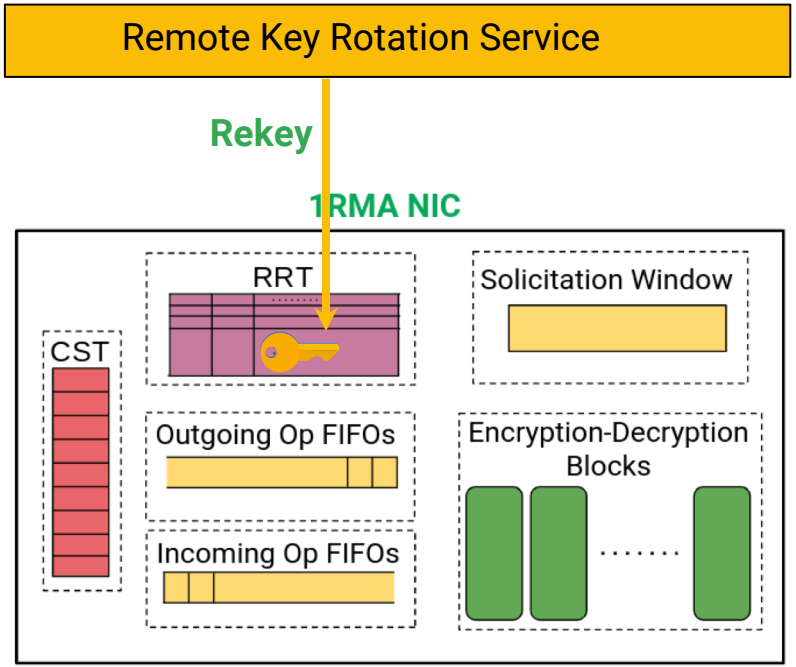

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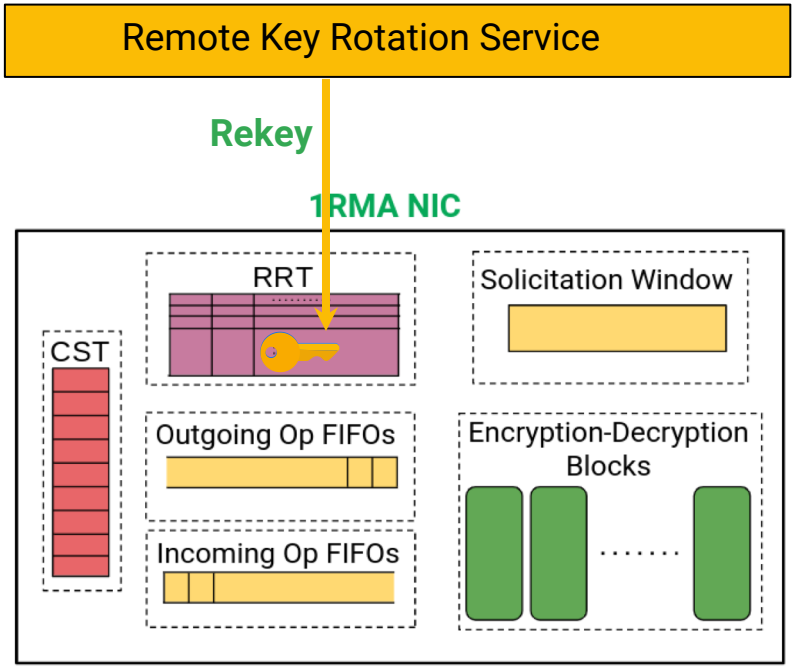

Enables key rotation

- **Without placing trust on local software stack**
- **Without involving local CPU**

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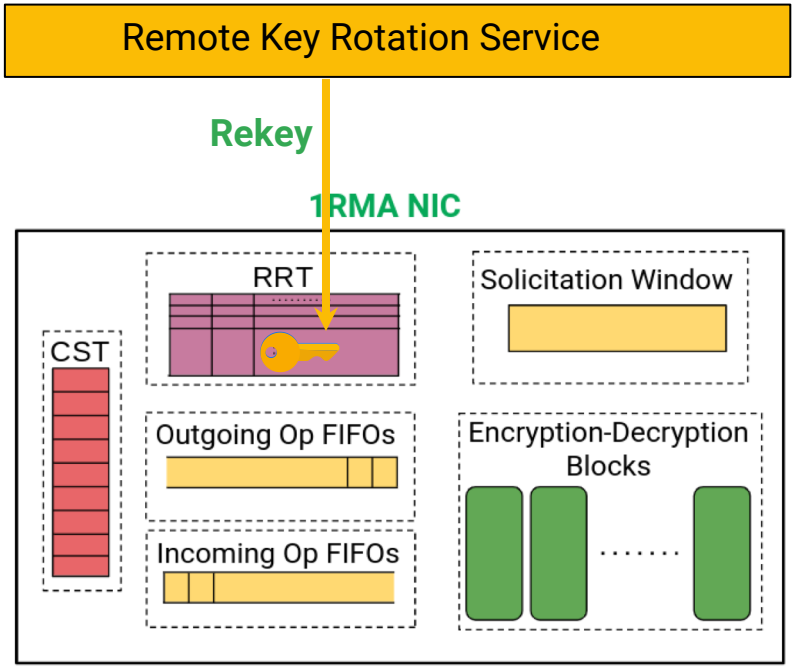

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Only ops corresponding to the affected memory region fail

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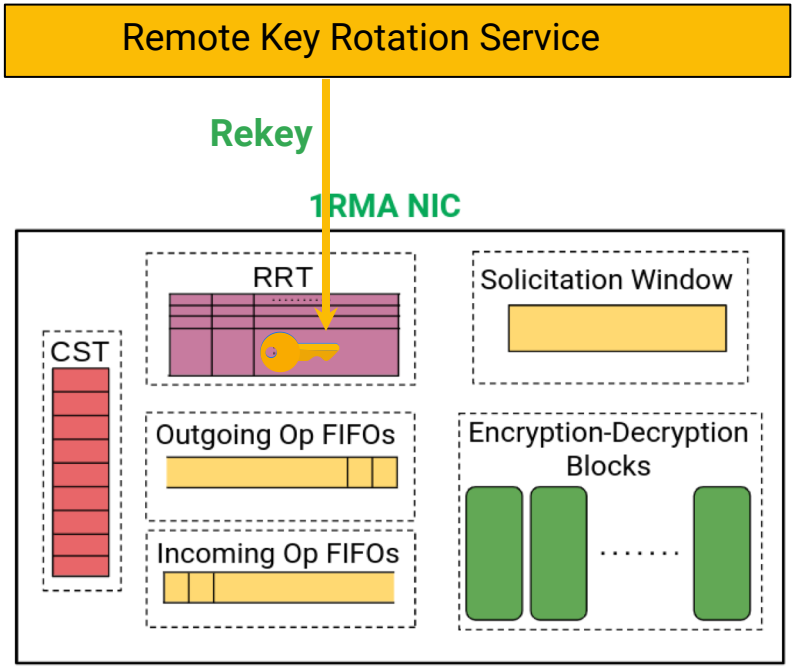


Enables key rotation

- **Without placing trust on local software stack**
- **Without involving local CPU**

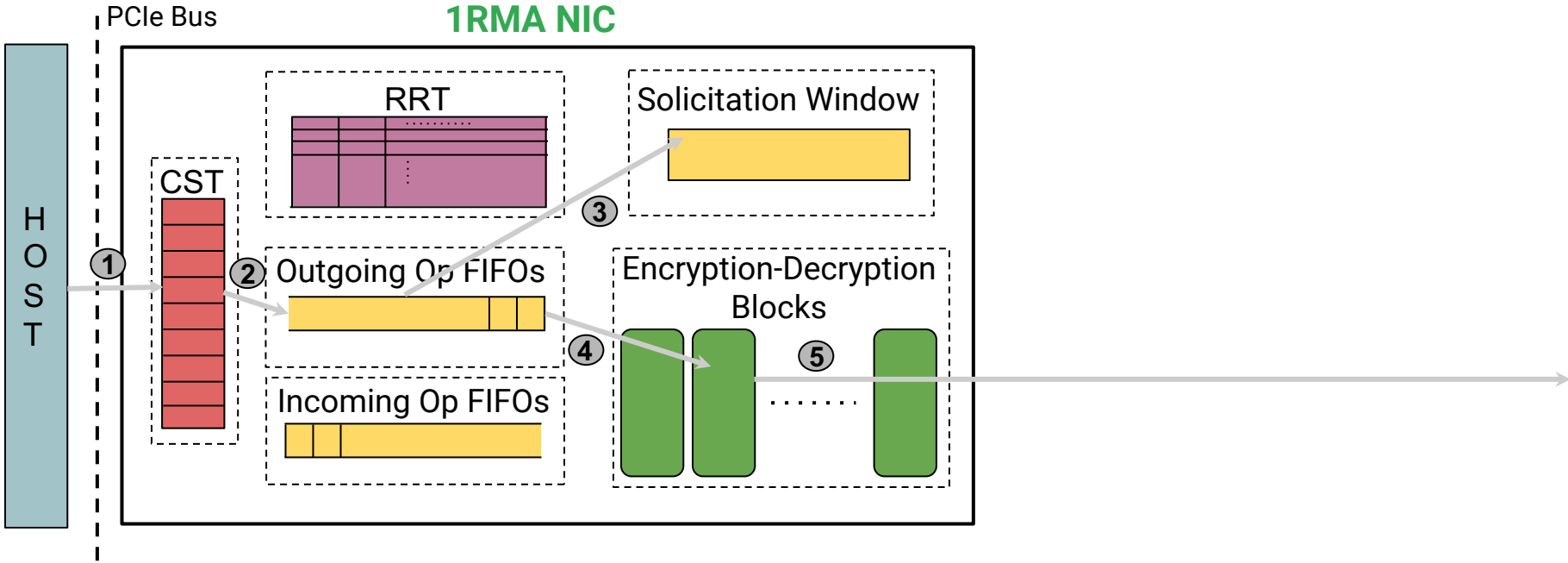
Only ops corresponding to the affected memory region fail

Unavailability period can be reduced to a single RTT

1RMA offers a **Rekey op** that provides **support for encryption key rotation**

Lifetime of a 2KB 1RMA READ Op

Lifetime of a 2KB 1RMA READ Op



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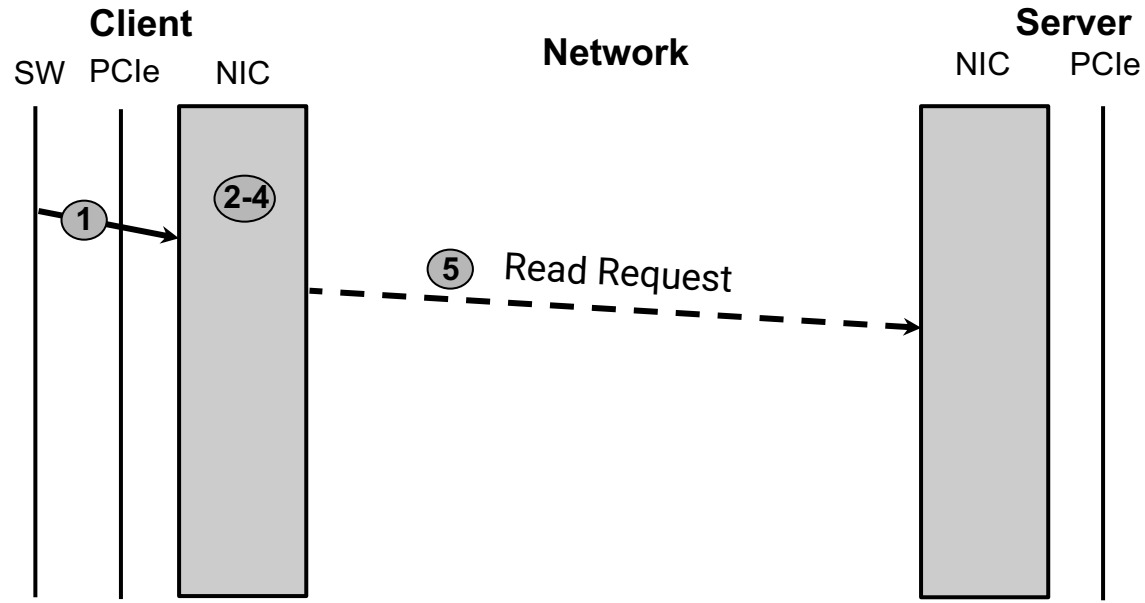

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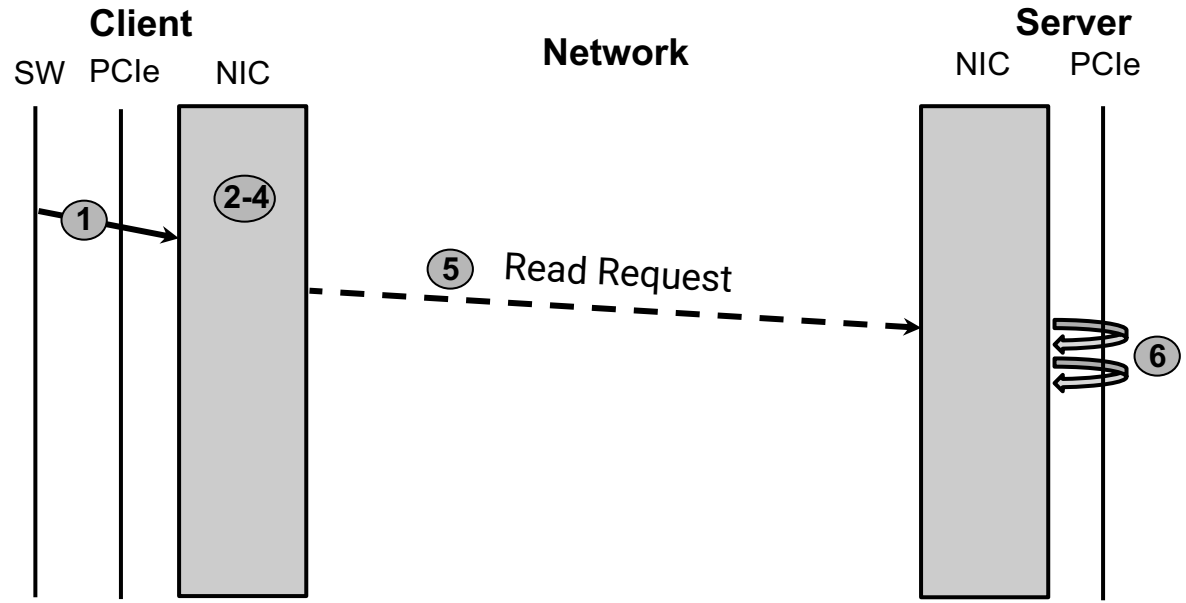

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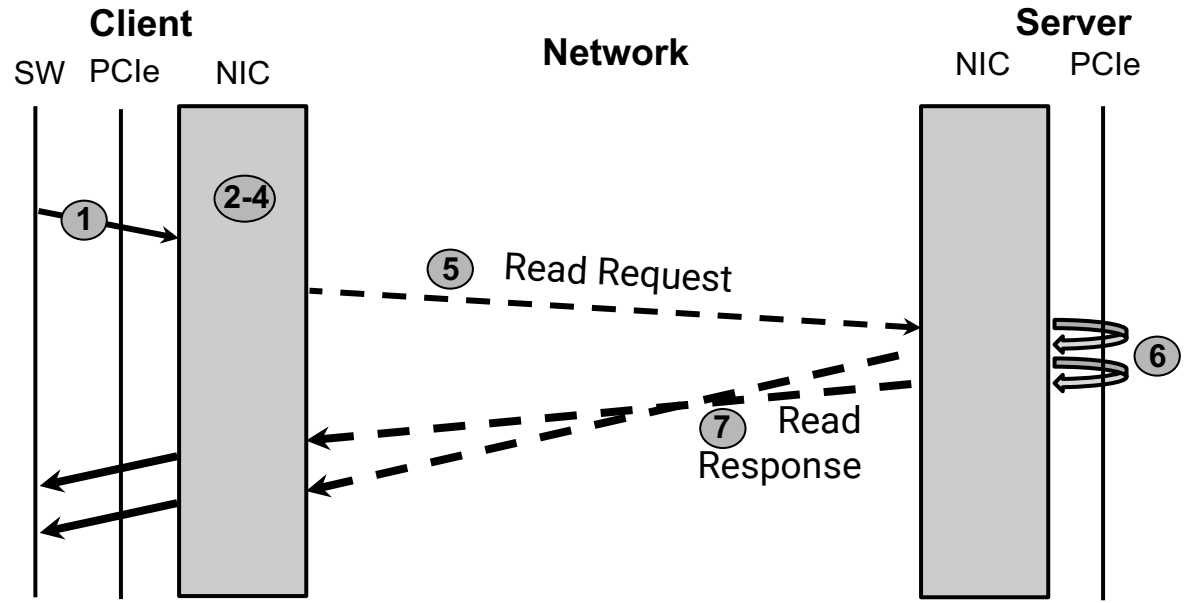

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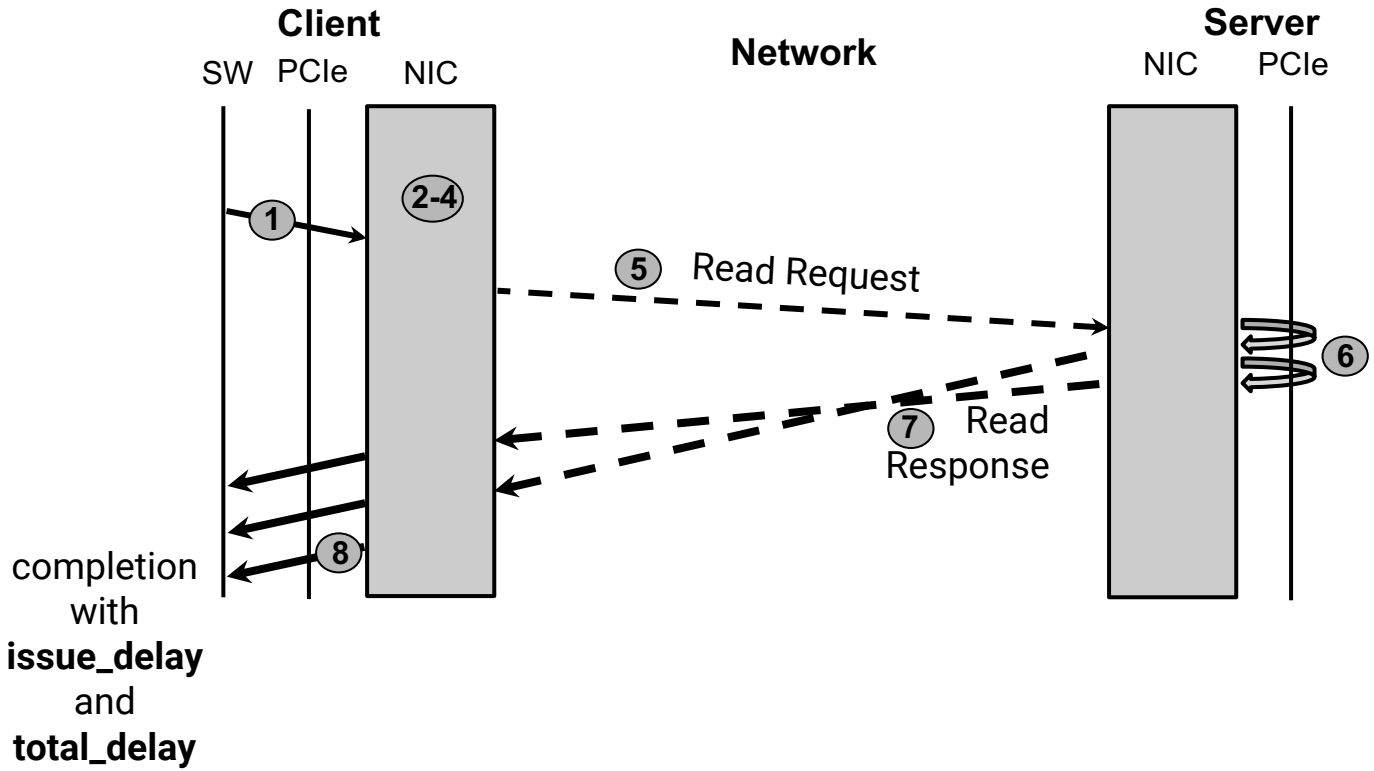

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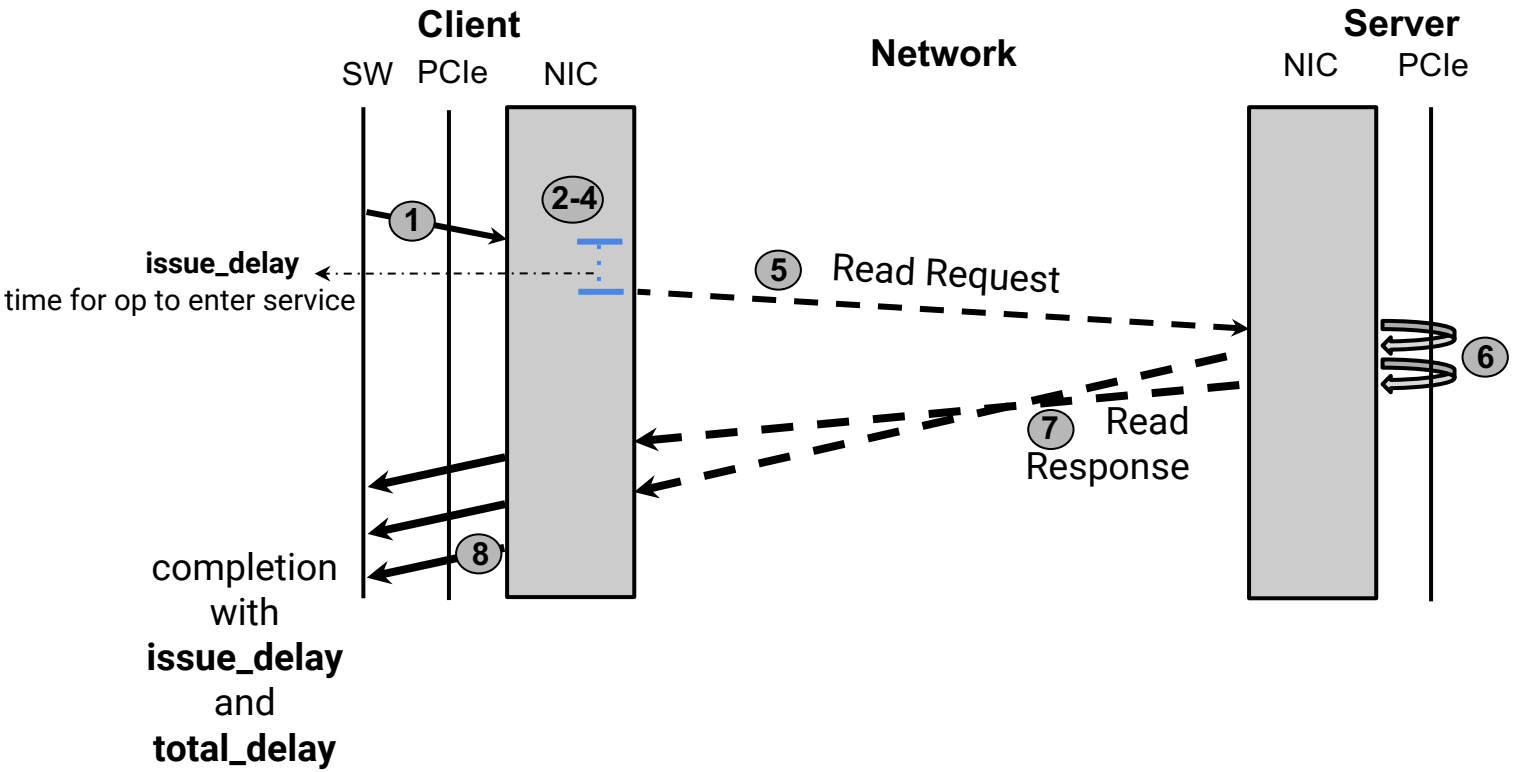

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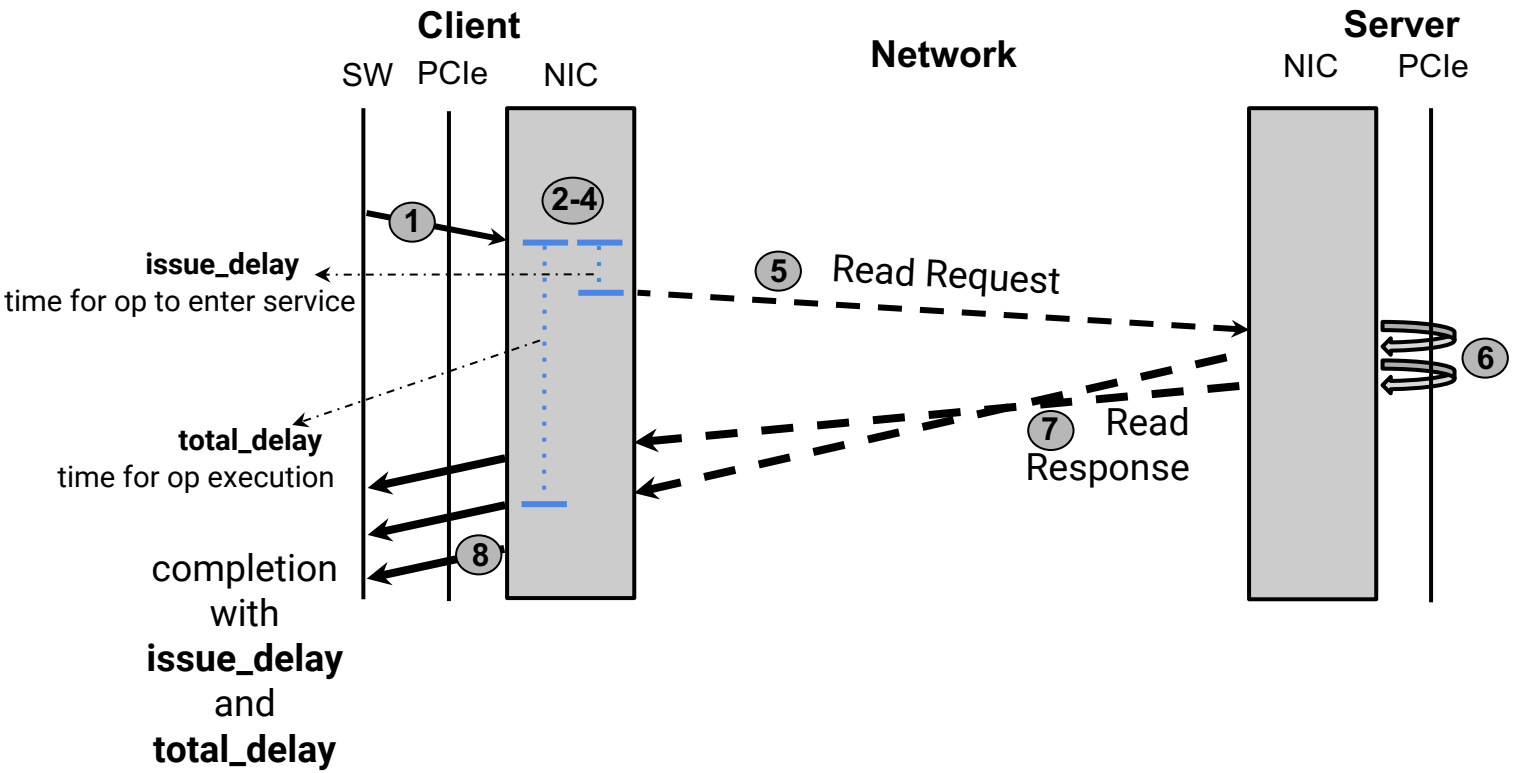
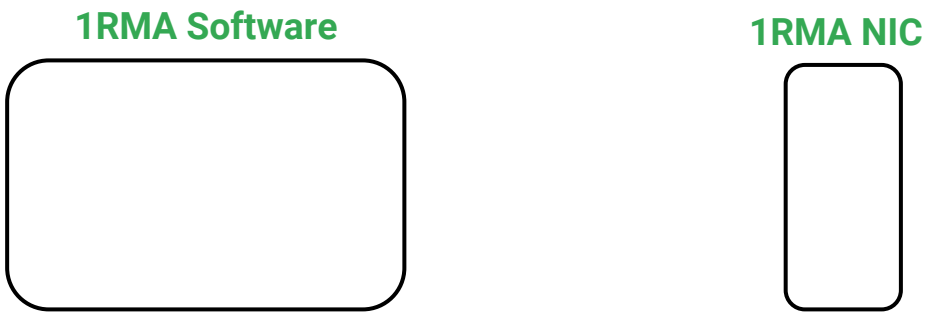


1RMA Key Idea #5: Software-driven Congestion Control



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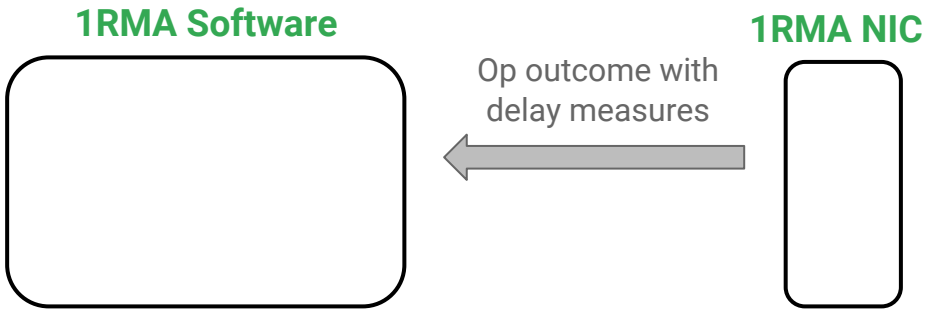

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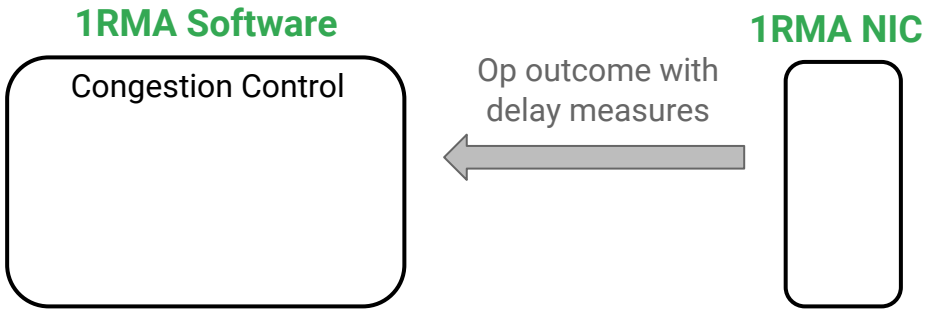
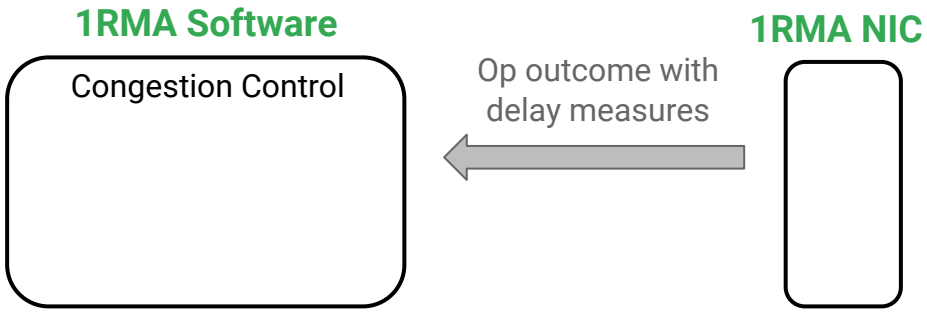


1RMA Key Idea #5: Software-driven Congestion Control

Uses delay as a congestion signal



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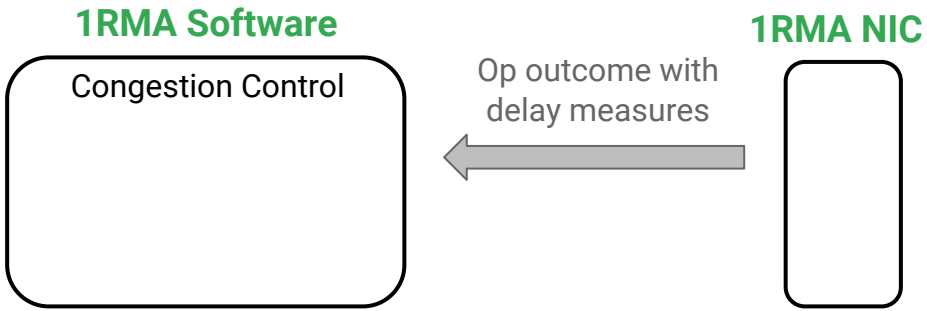
Uses delay as a congestion signal

Reacts separately to local and remote congestion

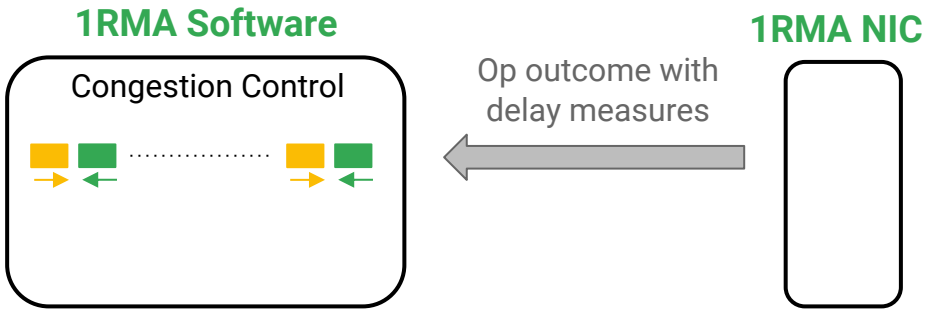


1RMA Key Idea #5: Software-driven Congestion Control

Uses delay as a congestion signal

Reacts separately to local and remote congestion

- Uses a CWND for each remote destination and direction



1RMA Key Idea #5: Software-driven Congestion Control

Uses delay as a congestion signal

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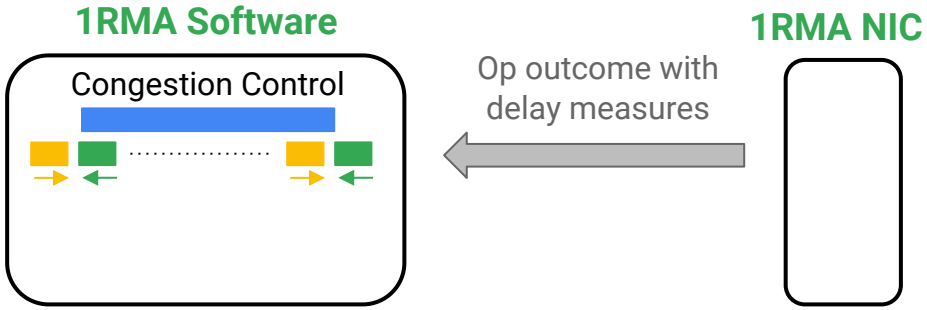

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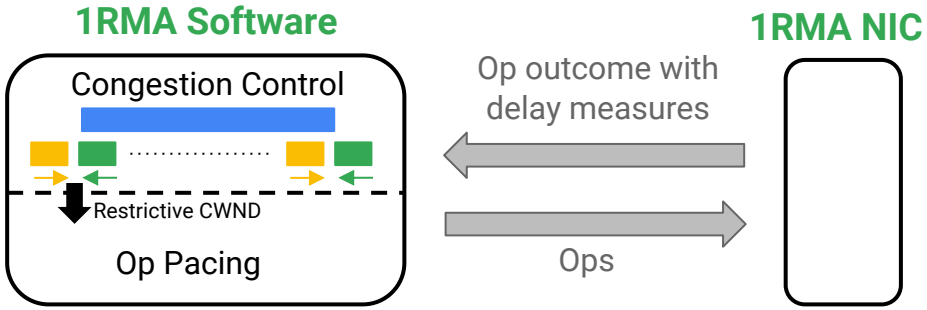
Op rate assigned using the more restrictive CWND



Software-driven Congestion Control

Simple AIMD controller based on whether measured delay exceed a target delay

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Algorithm 1: 1RMA CC reaction to local congestion.

Input: issue_delay, RTT
Output: cwnd_local

On Successful Op Completion
  $cwnd\_local\_old \leftarrow cwnd\_local$
  if $issue\_delay < TARGET\_DELAY$ **then**
    ▷ Additive Increase (AI)
    if $cwnd\_local \geq 1$ **then**
      $cwnd\_local \leftarrow cwnd\_local + \frac{AI}{cwnd\_local}$ ▷ $AI = 0.25$
    else
      $cwnd\_local \leftarrow cwnd\_local + AI$
    $cwnd\_local \leftarrow min(cwnd\_local, CWND\_MAX)$

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    $cwnd\_local \leftarrow min(cwnd\_local, CWND\_MAX)$
  else
    ▷ Multiplicative Decrease (MD)
    if *no decrease in the last RTT time* **then**
      $delta \leftarrow issue\_delay - TARGET\_DELAY$;
      $cwnd\_local \leftarrow$ ▷ $MD = 0.5, \beta = 0.8$
        $max(1 - \beta \cdot (\frac{delta}{issue\_delay}), MD) \cdot cwnd\_local$;
      $cwnd\_local \leftarrow max(cwnd\_local, CWND\_MIN)$;

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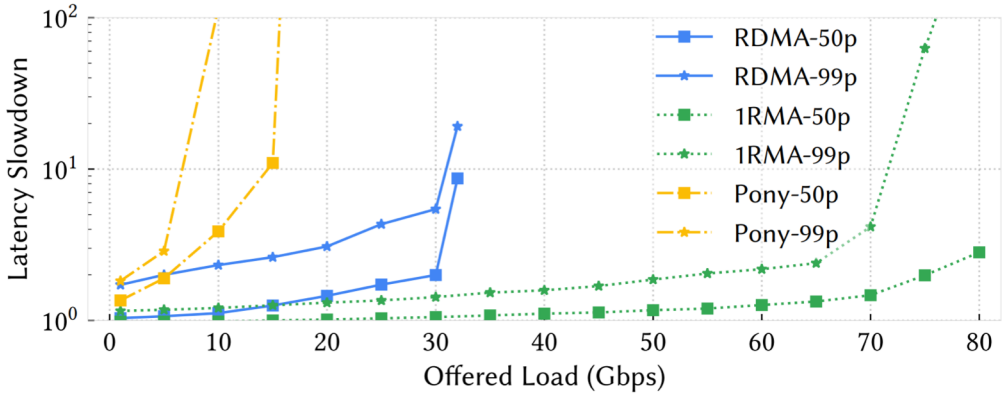
    - $cwnd\_local \leftarrow max(cwnd\_local, CWND\_MIN)$;

On Dispatch Timeout
- **if** *no decrease happened in the last RTT time* **then**
  - $cwnd\_local \leftarrow$ ▷ $TIMEOUT\_DECR = 0.1$
    $TIMEOUT\_DECR \cdot cwnd\_local$;
  - $cwnd\_local \leftarrow max(cwnd\_local, CWND\_MIN)$

Evaluation

How does 1RMA perform relative to state-of-the-art?

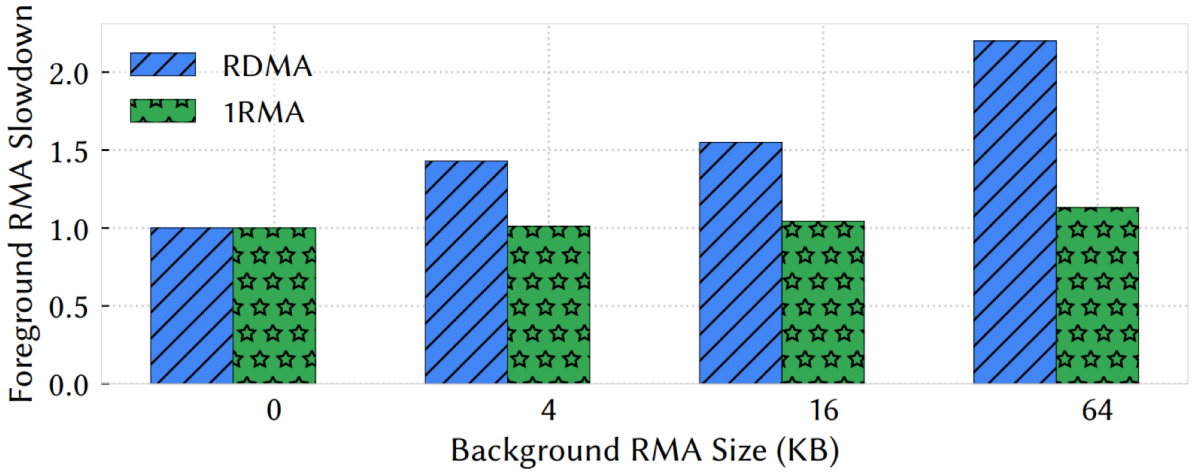
Workload: 40-node uniform random traffic pattern
Baselines: Pony Express(sosp19) and RDMA



1RMA experiences the least latency slowdown for comparable offered load

Does 1RMA provide isolation and ensure prioritization?

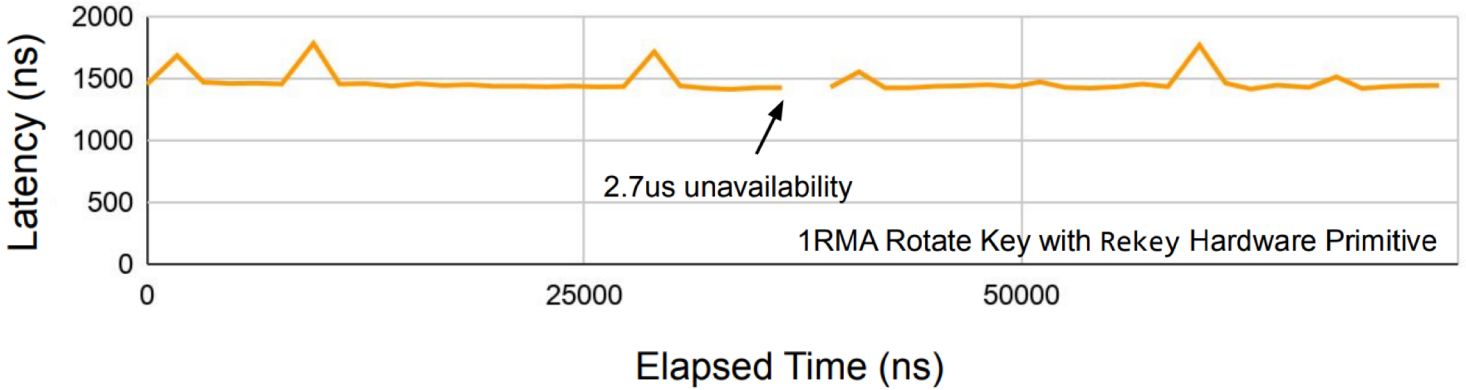
Point-to-point workload consists of small 64B foreground transfers and one outstanding large background transfer



RDMA introduces delays proportional to the background RMA size while 1RMA experiences minimal slow down

What impact does 1RMA's Rekey Op have on availability?

Point-to-point workload consists of small reads and server does encryption key rotation

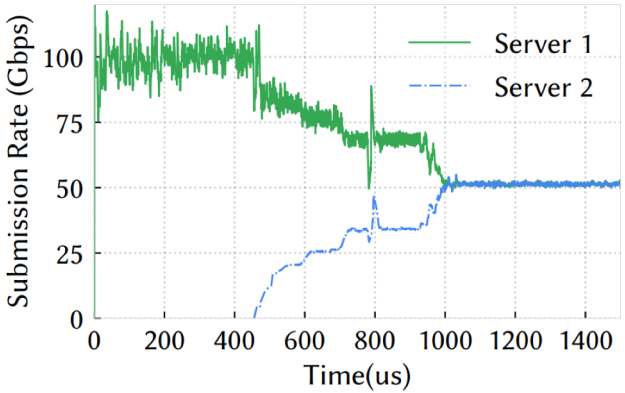


1RMA experiences minimal impact of availability during key rotation

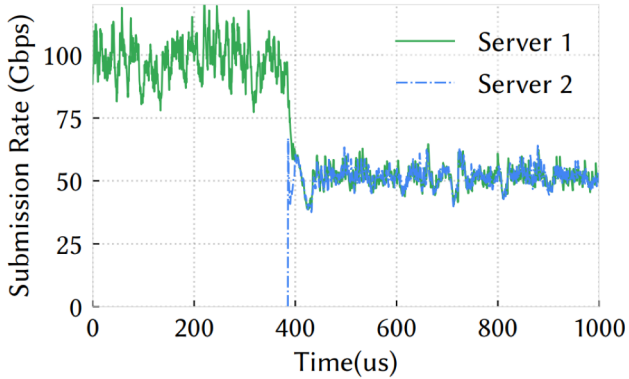
What role does local congestion reaction play?

Client initiates long-running transfers of 4MB reads with one server in the beginning and another server at around 400 us

No separate reaction to local congestion



Separate reaction to local congestion



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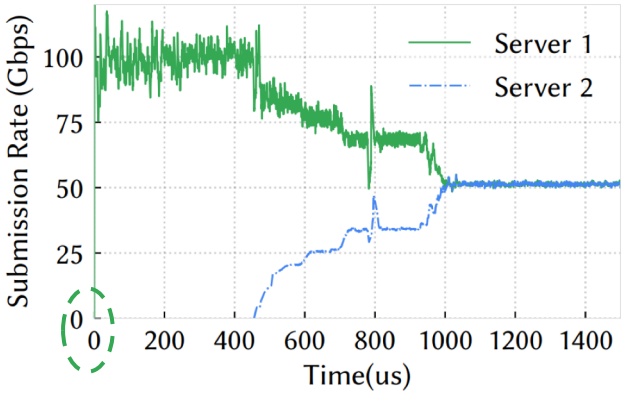
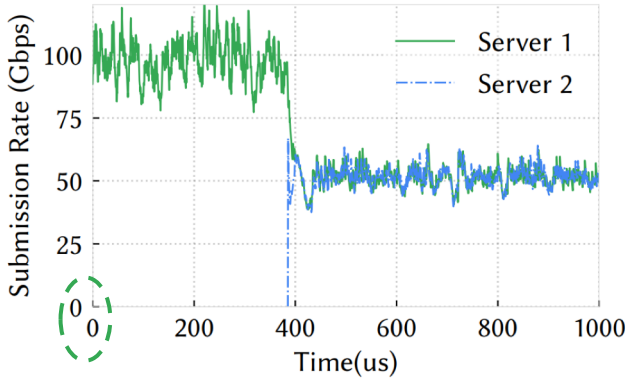


Separate reaction to local congestion



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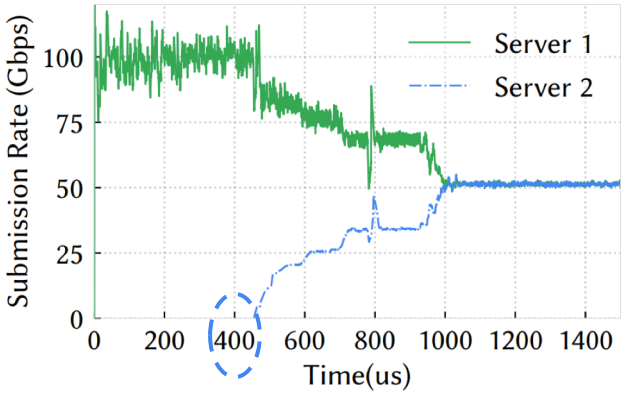

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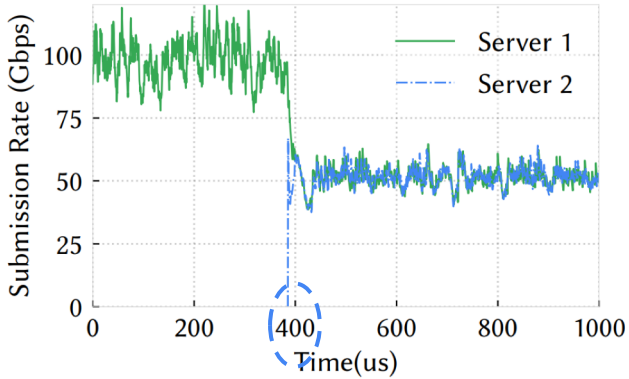

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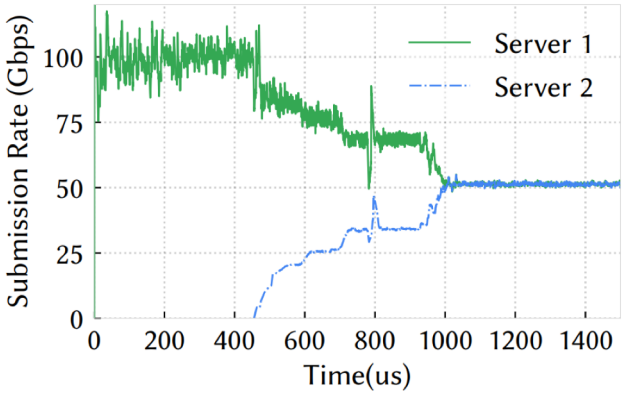

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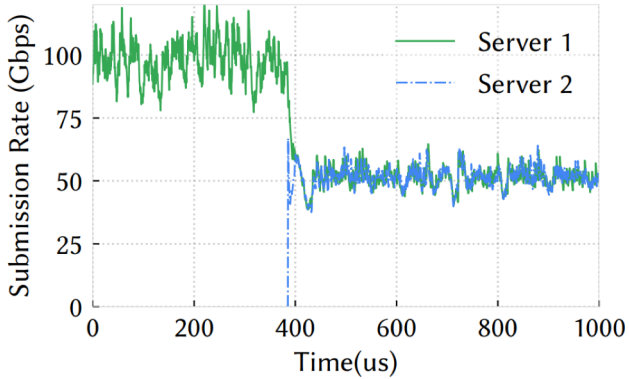

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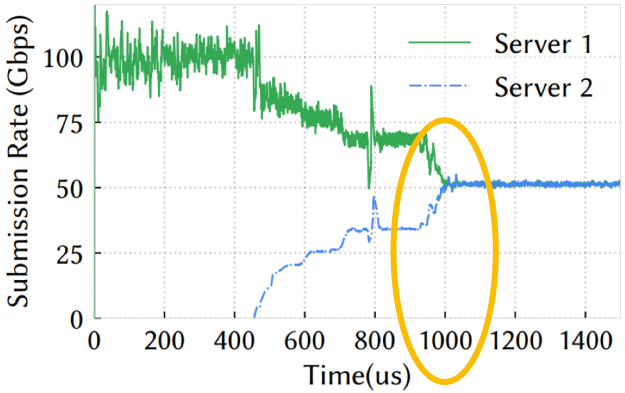

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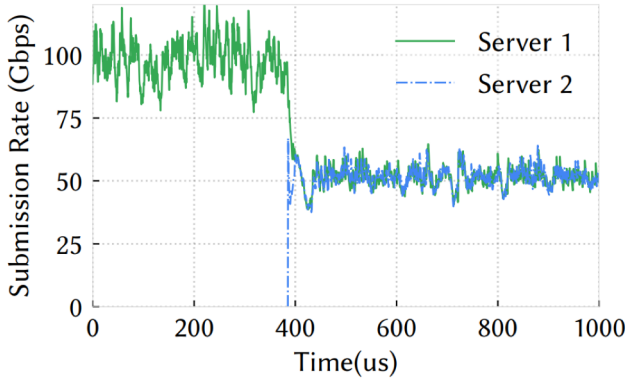

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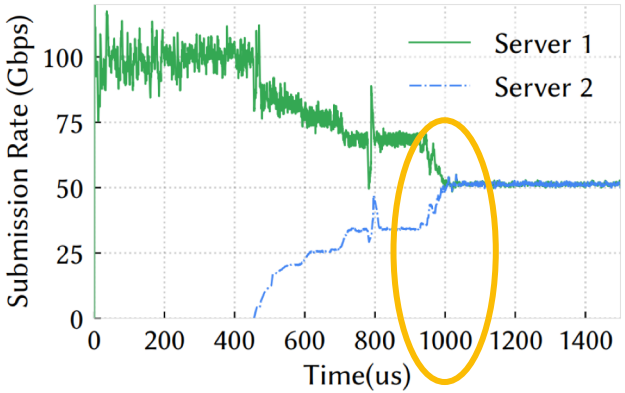

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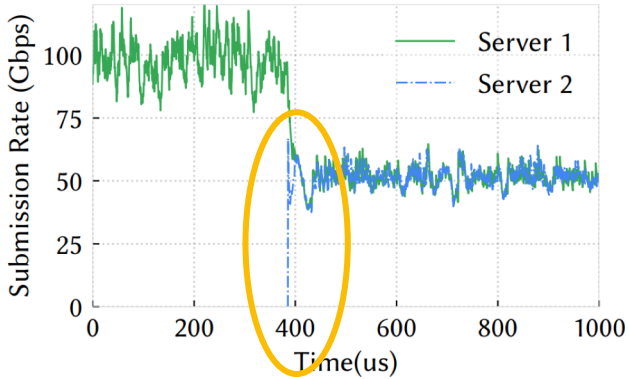
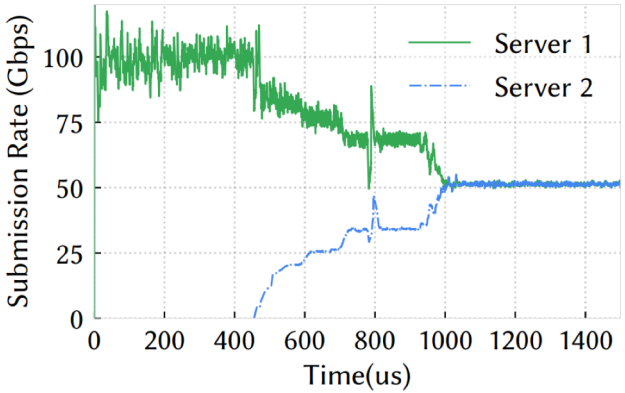


Reacting *separately* to local congestion converges 20x faster

What role does local congestion reaction play?

No separate reaction to local congestion



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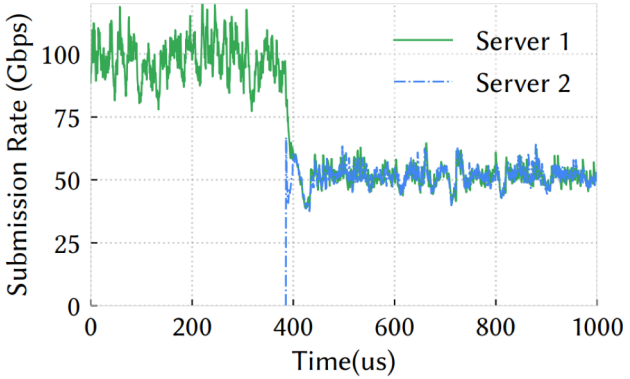

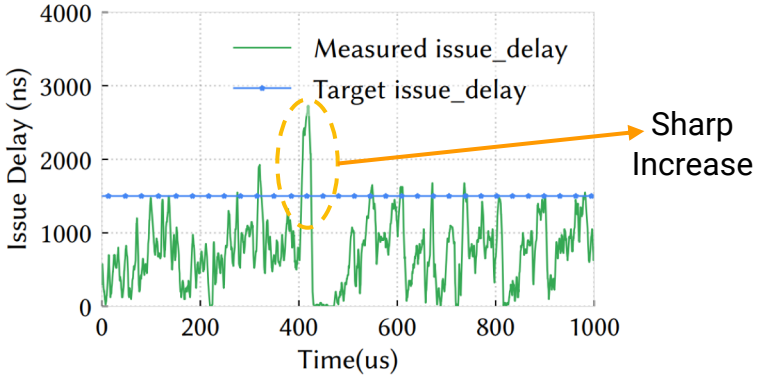

Summary

Existing RDMA technologies ill-suited to multi-tenant datacenters

- Connection-orientedness
- Complex policies in hardware

1RMA re-envisions RMA for multi-tenant datacenters

- 1RMA NIC hardware
  - Connection-free and fixed-function with explicitly allocated resources
  - Aids software by provided delay measurements and fast failure notifications
- 1RMA software
  - Implements congestion control and op management (e.g., failure recovery)

Thank you!

1RMA: Re-envisioning Remote Memory Access for Multi-tenant Datacenters

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